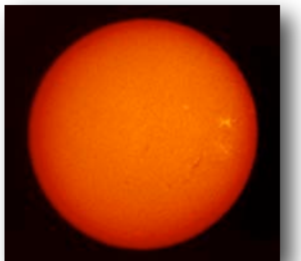
Studying Terrestrial Neutrinos with KamLAND (and NERSC!)

^{7}Be solar neutrino



Neutrino Astrophysics

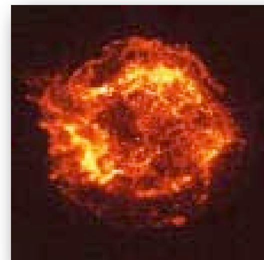
geo-neutrino

Neutrino Geophysics

reactor neutrino

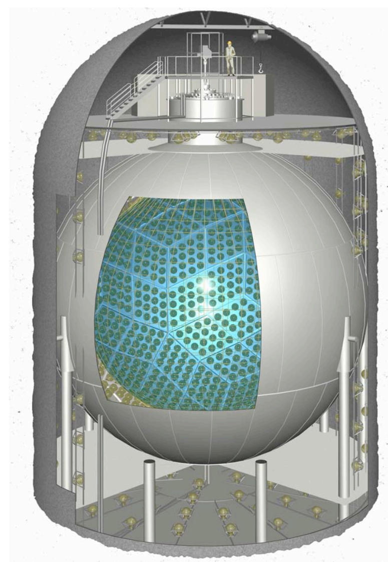
Neutrino Physics

supernova, relic neutrino,
solar anti-neutrinos etc.



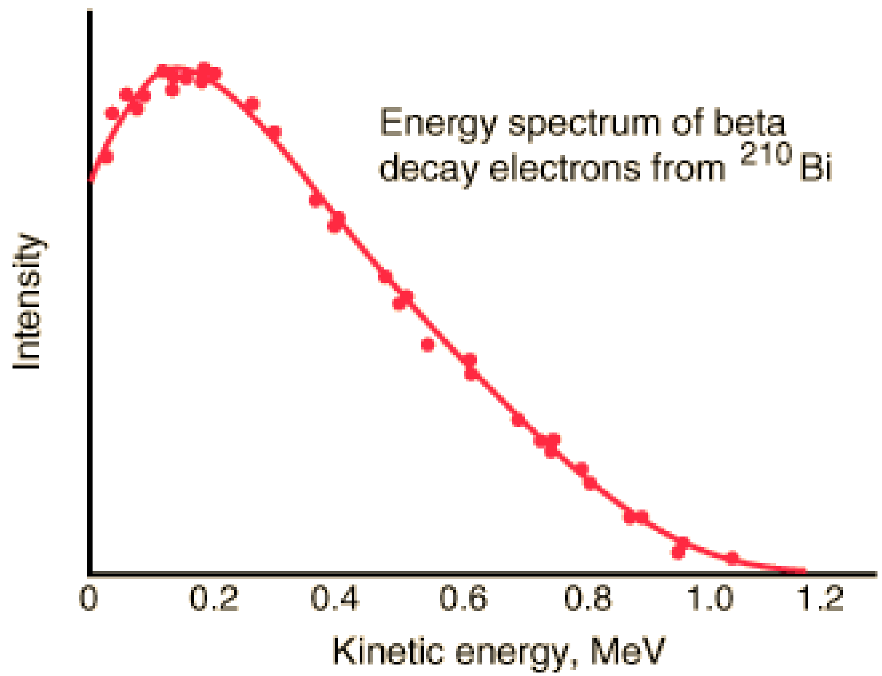
Neutrino Cosmology

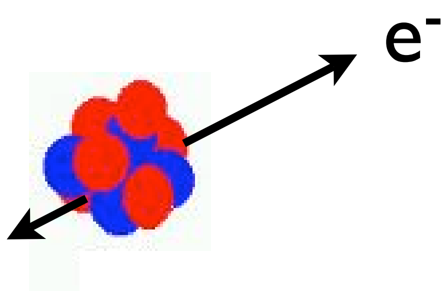
Patrick Decowski
UC Berkeley



About Neutrinos

The Neutrino

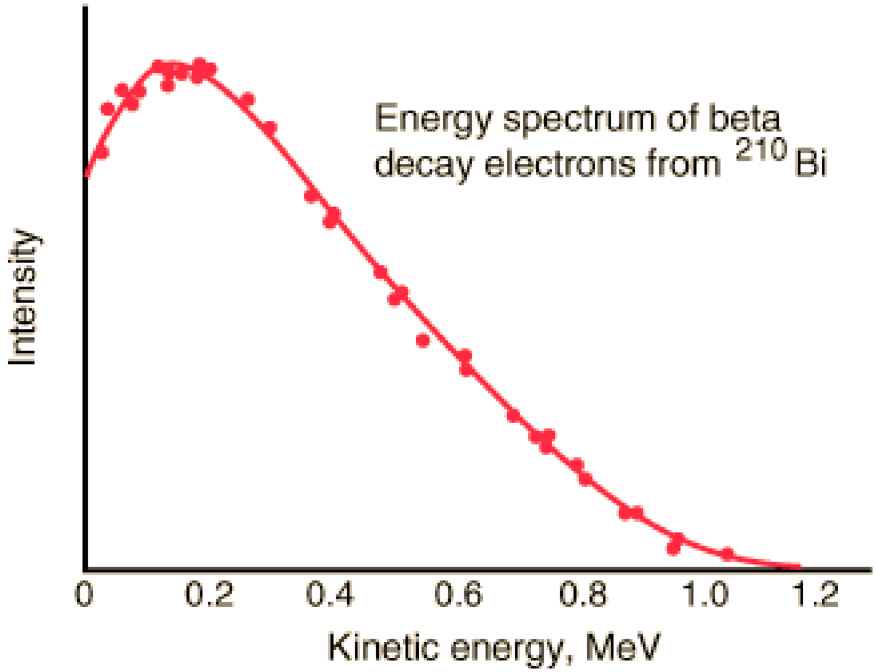


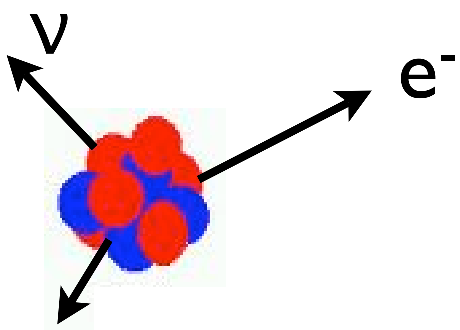


Not possible to reconcile with above spectrum

I have hit upon a desperate remedy...
-W. Pauli

The Neutrino





I have hit upon a desperate remedy...
-W. Pauli

Neutrino part of Standard Model

- Invented to save E, **P**, **L** conservation in β-decay
  - "Invisible": very weakly interacting
  - Chargeless
  - Spin 1/2 (a fermion)
  - Very small mass: <1/100000 smaller mass than electron
  - 100 billion neutrinos from the Sun pass your fingernail every second!

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

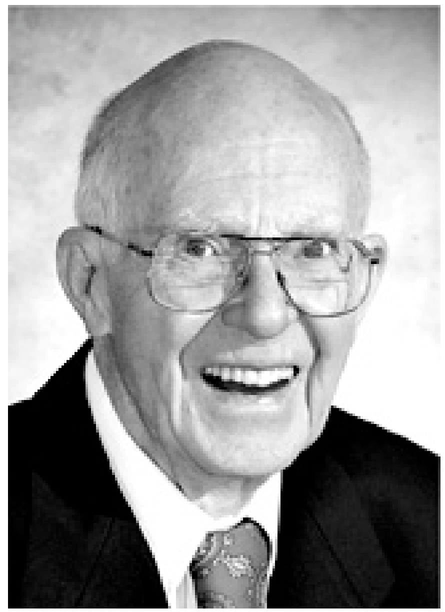
Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

2002 Nobel Prize in Neutrino Studies

- Over the years, the neutrino has become a key particle in the Standard Model
- $m_\nu > 0$: first "physics beyond the Standard Model"
- 2002 Nobel Prize: ν astrophysics

"For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."

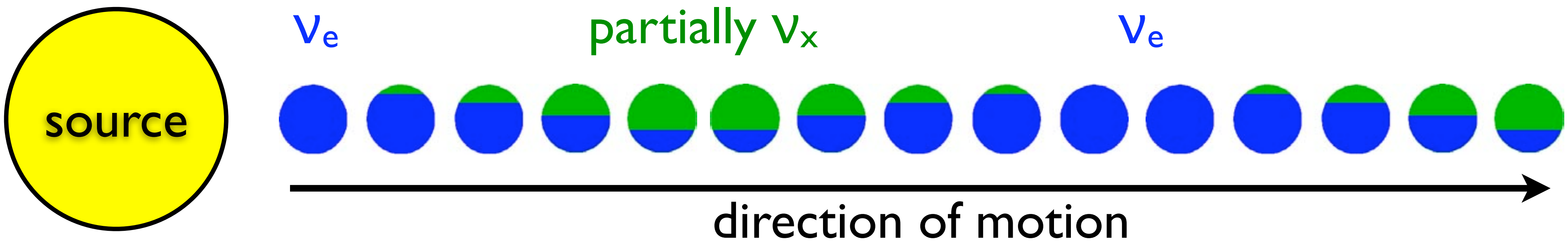


Raymond Davis Jr.

Masatoshi Koshiba

Images from nobelprize.org

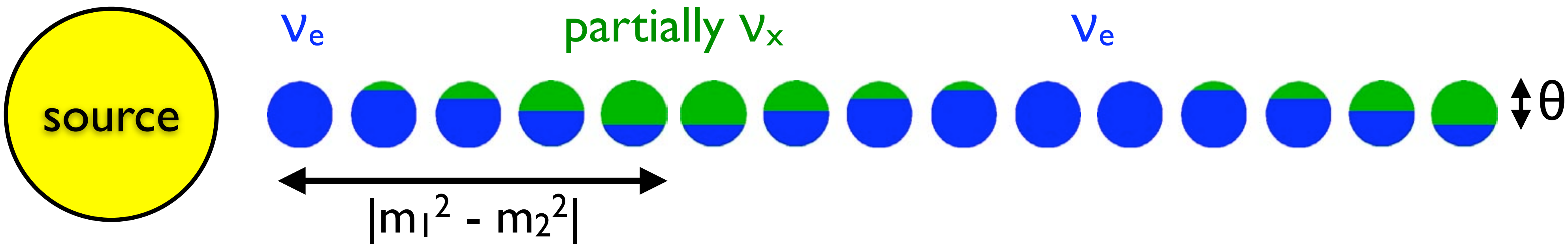
Neutrino Mixing and Oscillation



In 1960-1996 indications that neutrinos have quite complex behavior: change "flavor" with time

Since neutrinos experience time, they must have mass

Neutrino Mixing and Oscillation

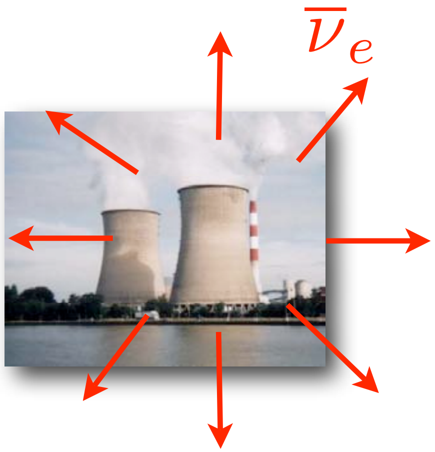


$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

From your Quantum Mechanics course:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

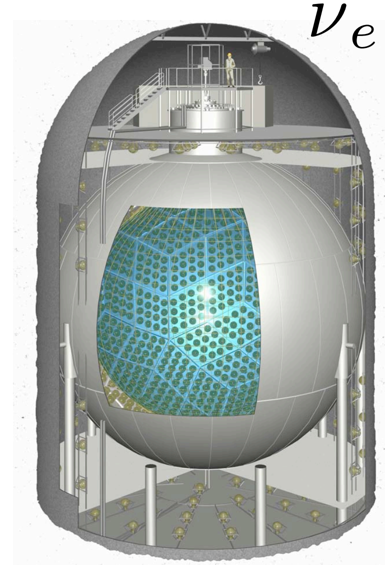
Reactor Neutrino Experiments



$\overline{\nu}_e$**?** →

$\overline{\nu}_x$**?** →

$\overline{\nu}_e$



$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27\Delta m^2 L}{E}$$

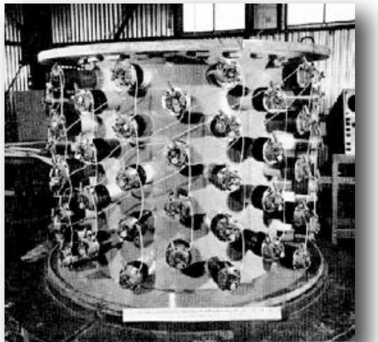
L

Few MeV anti-neutrinos, energy too low to produce μ or τ

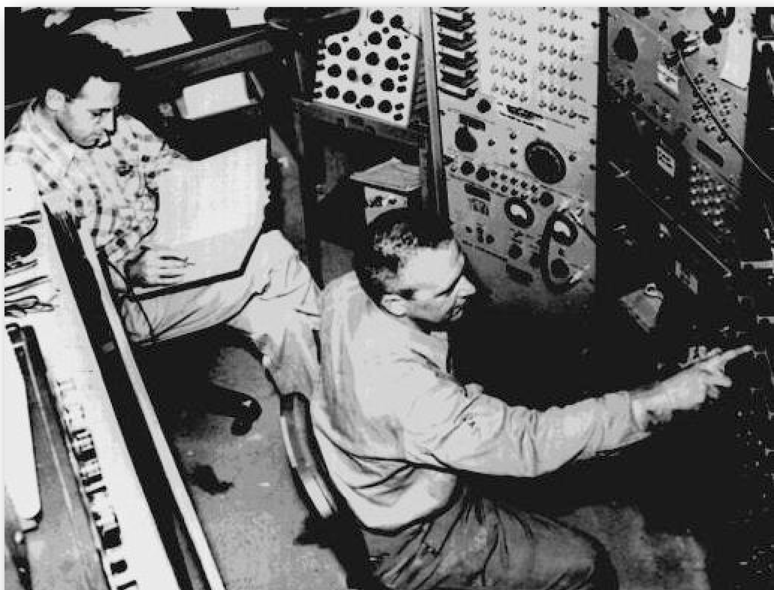
➡ disappearance experiments

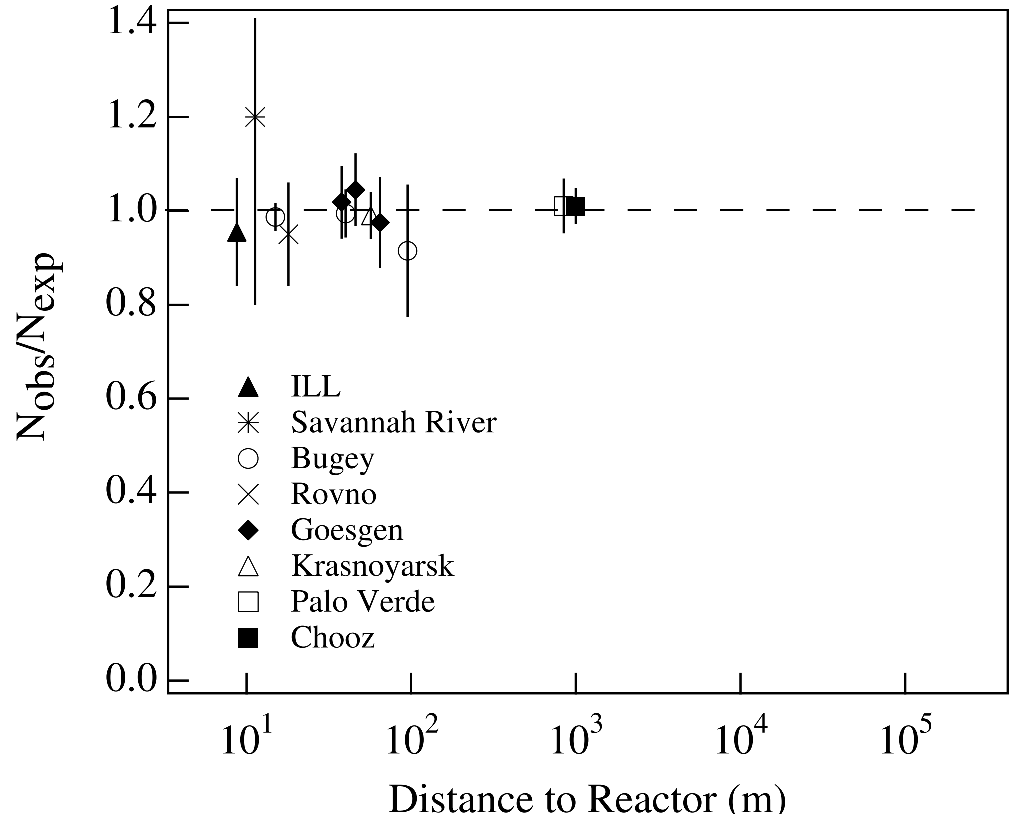
Oscillation searches with Reactors

Reactors have played an important role in the early history of neutrinos and in neutrino oscillation searches: 1953 - Present



Project Poltergeist
(Reines & Cowan 1953)





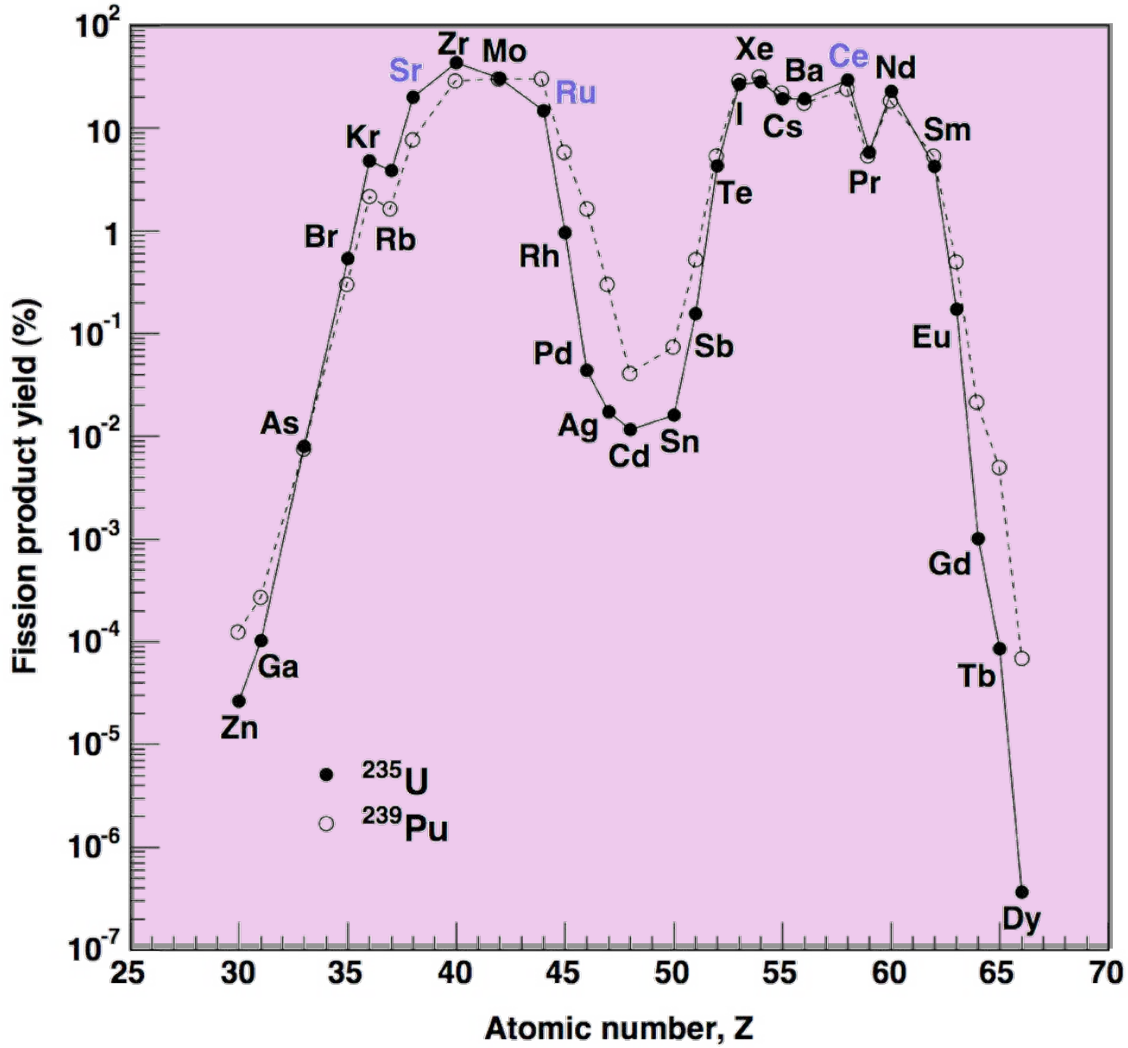
- Many different experiments
  - Baselines up to 1km
  - No evidence for $\overline{\nu}_e$ disappearance

About
Reactor Anti-Neutrinos

From the 1955 Movie with same title

Reactor Anti-Neutrinos

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



The stable products most likely from Uranium fission:

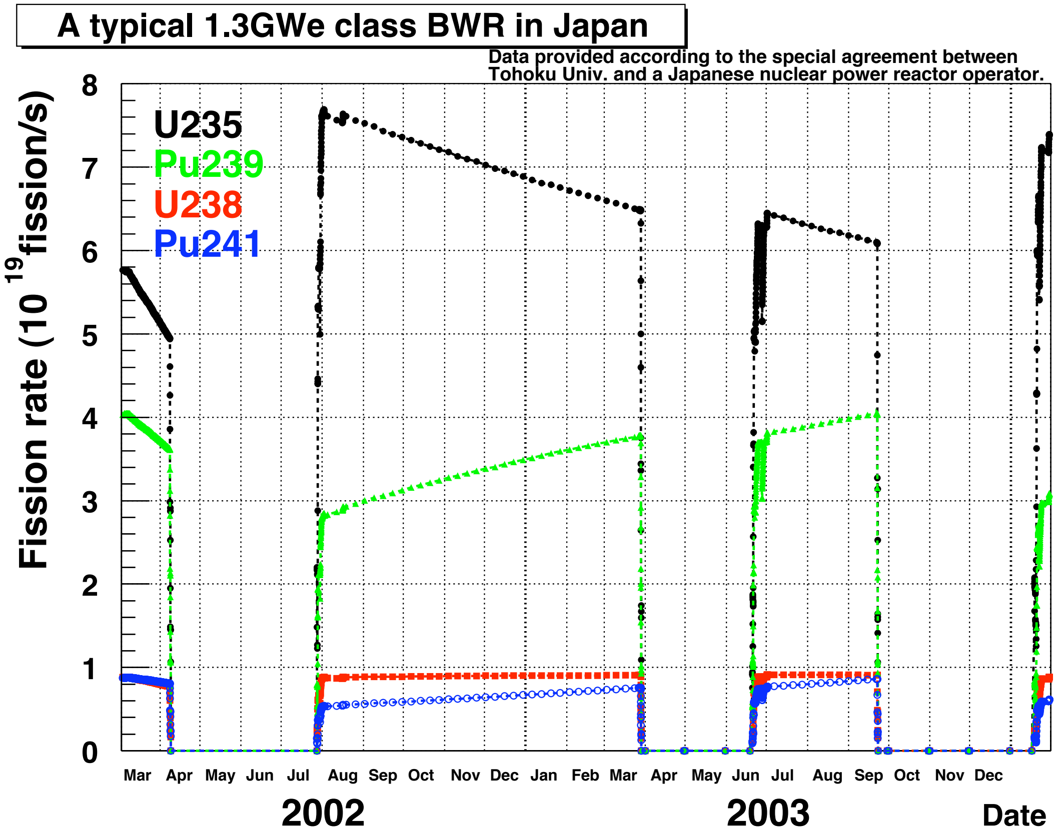
$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$

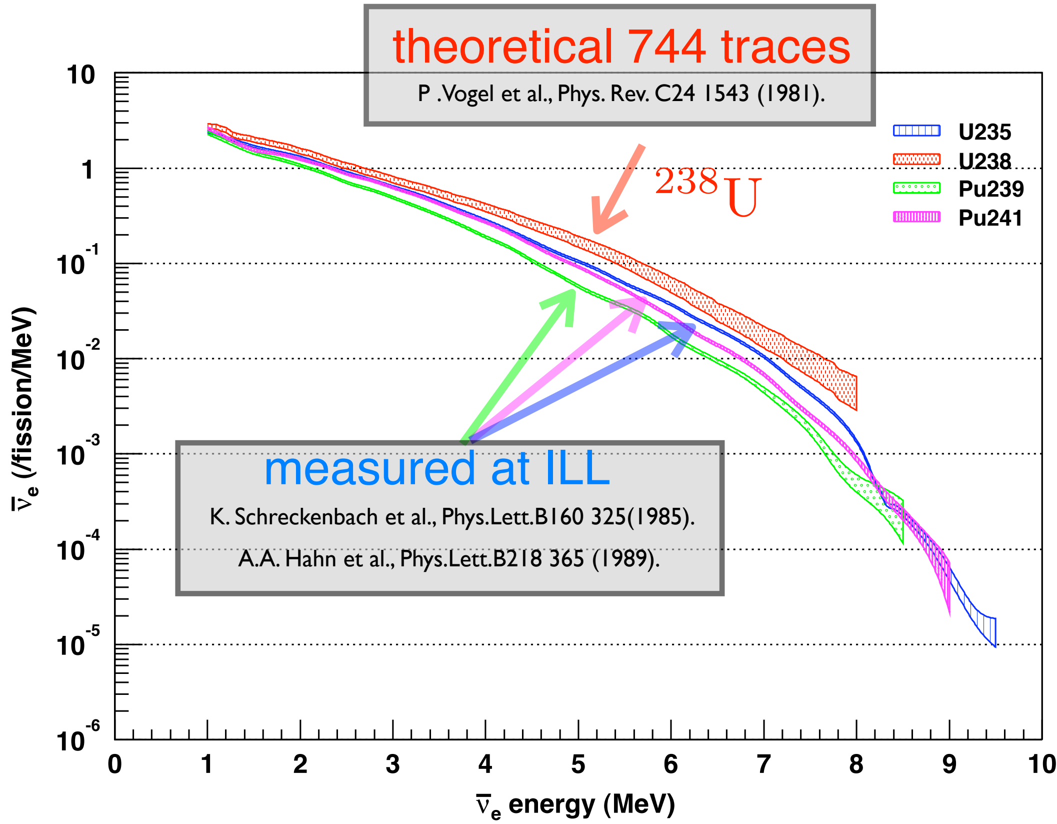
Together 98 protons and 136 neutrons

6 neutrons have to β-decay to reach stable matter, producing 6 $\overline{\nu}_e$ / fission

Calculating Neutrino Spectra

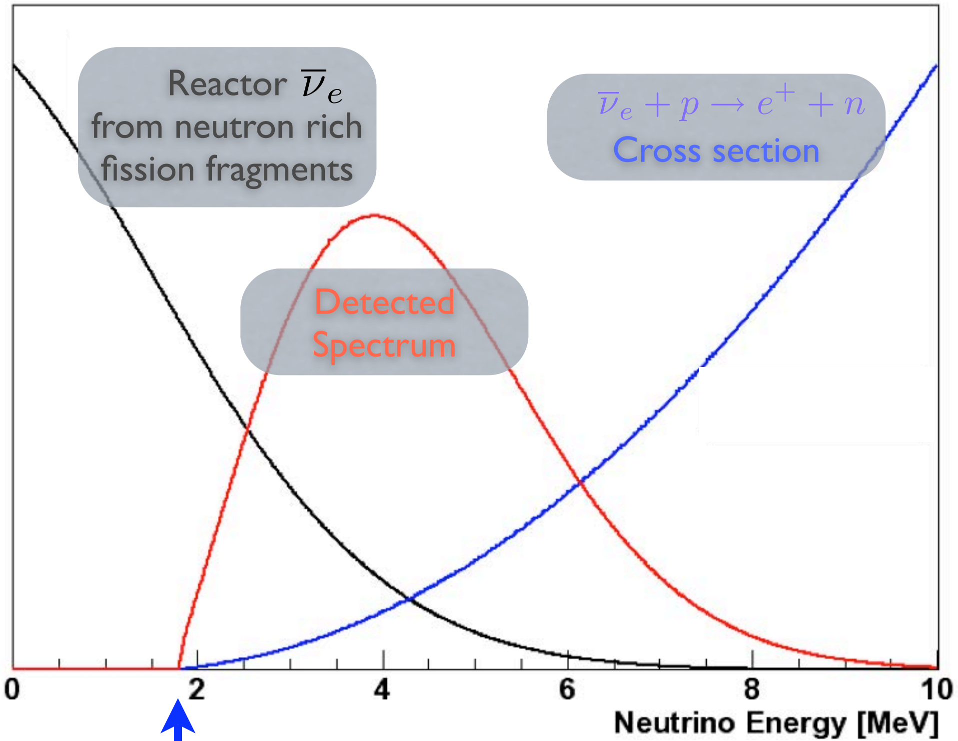
Only 4 isotopes relevant



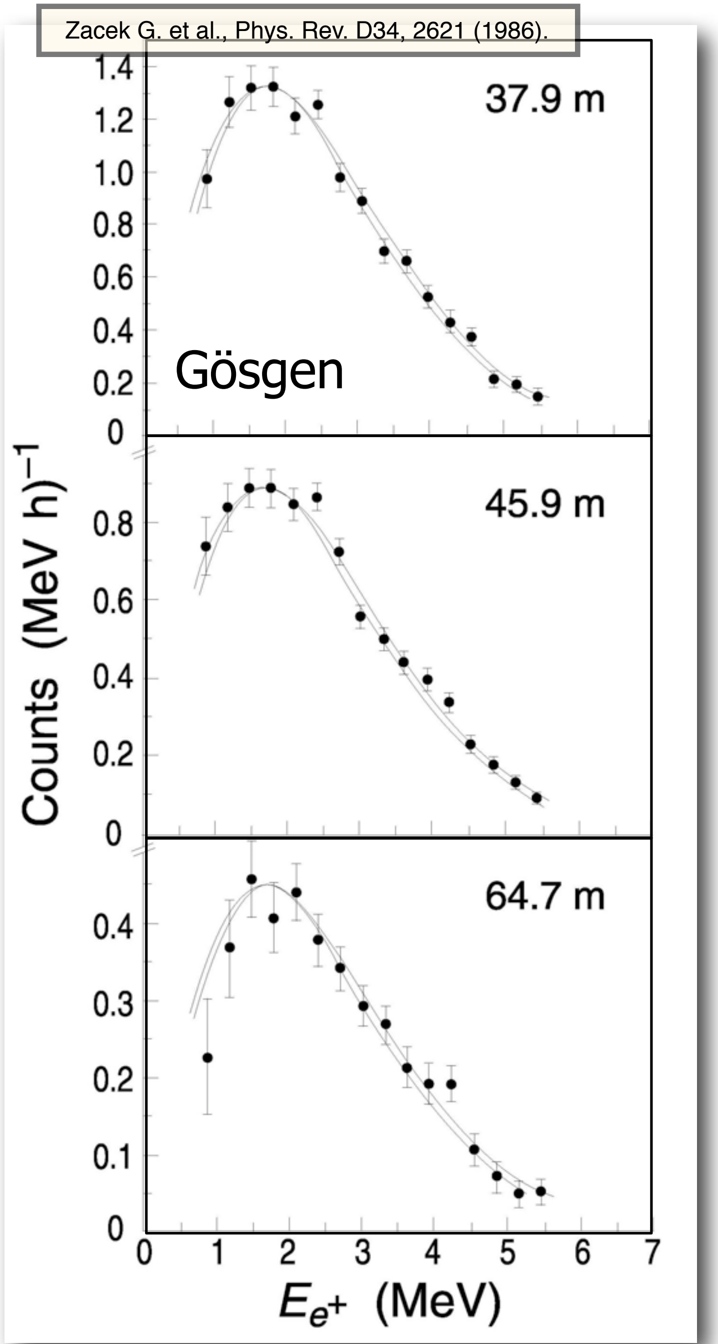


- Fission rates are provided by reactor companies
  - Chiefly function of thermal power
  - Weak function of inlet T: 10% → ~0.15% rate change

Detected Reactor Spectrum



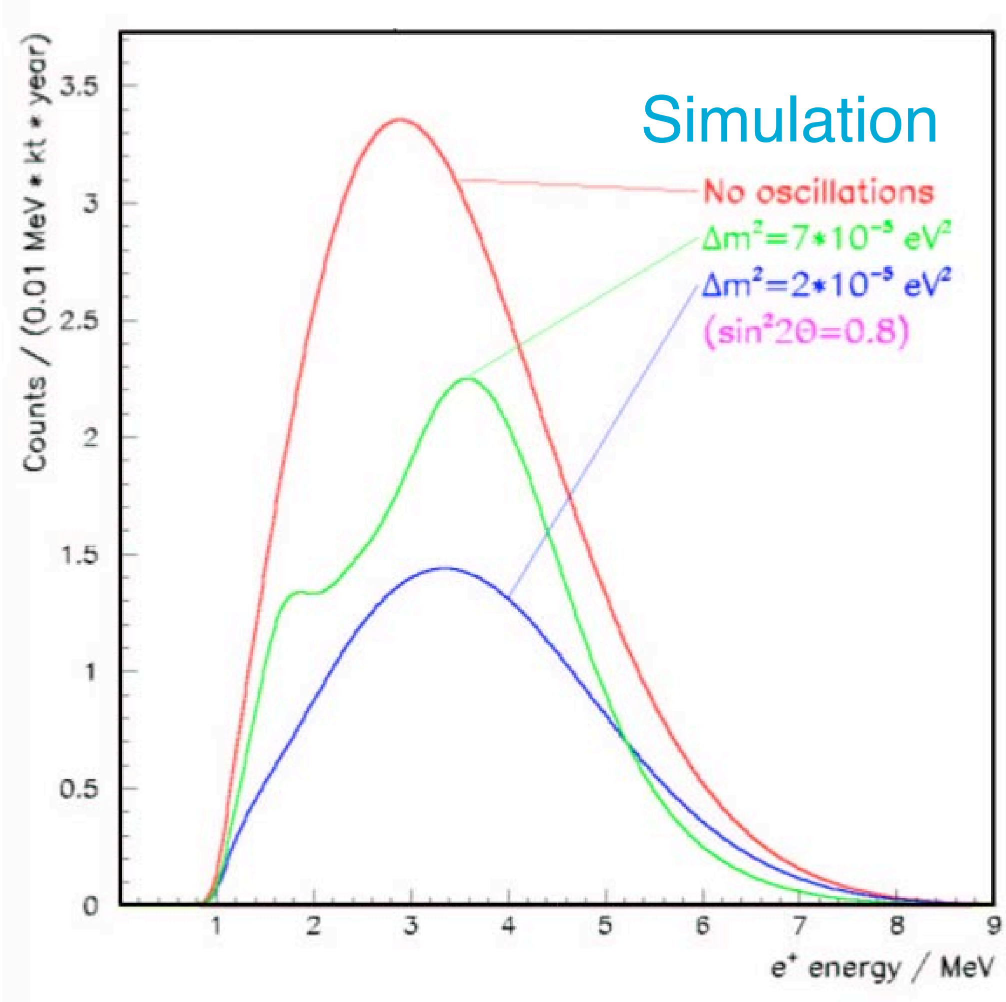
1.8MeV threshold in Inverse Beta Decay

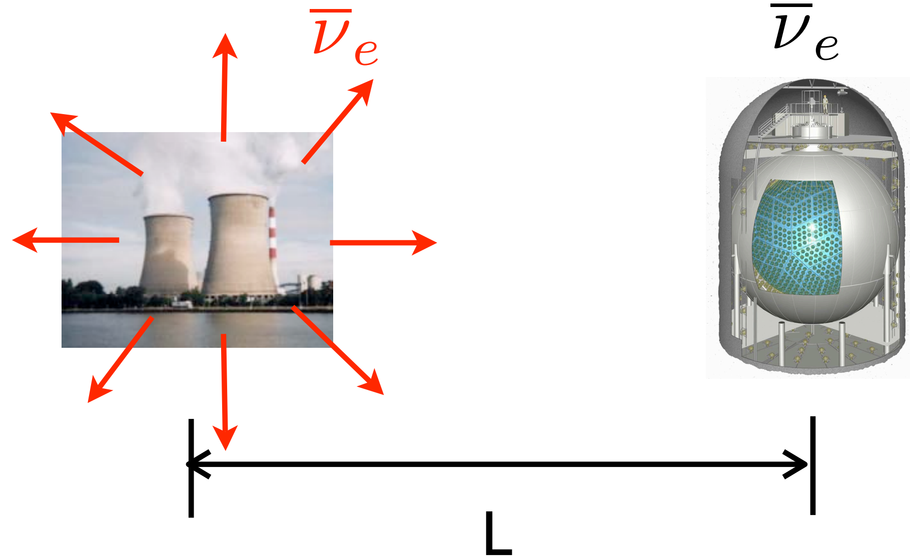


- In practice, only 1.5 neutrinos/fission detectable
- Calculated spectrum has been verified to 2% accuracy in past reactor experiments

No near detector necessary!

Distortion of Spectrum





$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

Neutrino oscillation changes both the overall normalization and the shape of the spectrum

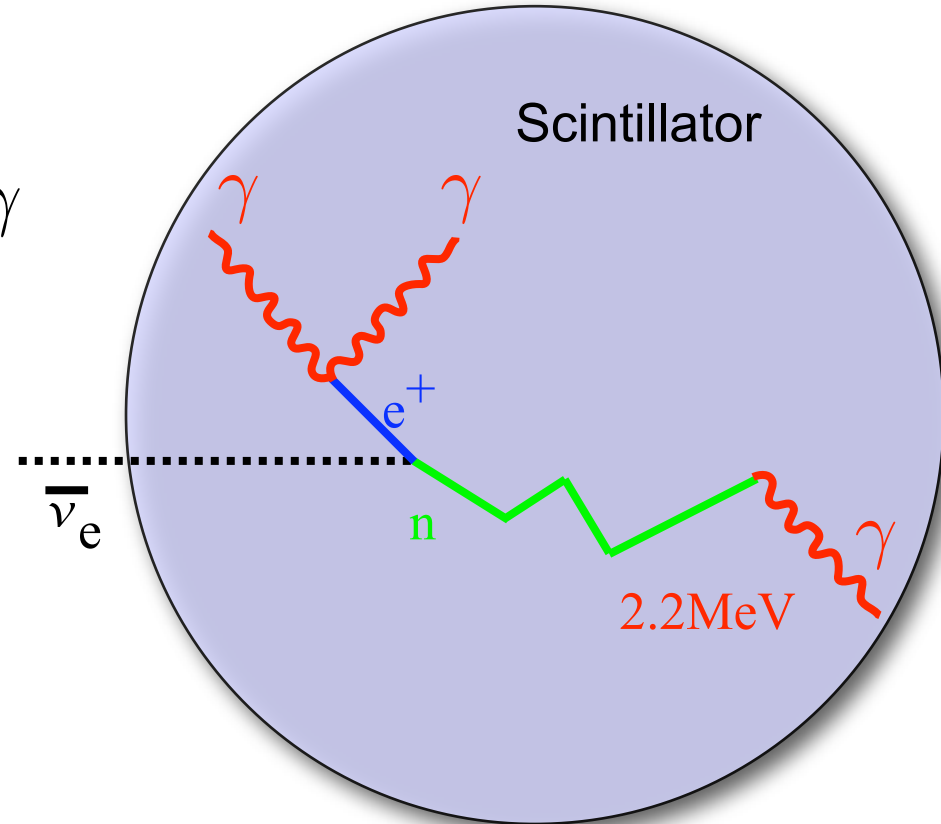
Anti-Neutrino Detection Method

Reaction process: Inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

Scintillator is both target and detector



- Distinct two step process:
  - prompt event: positron

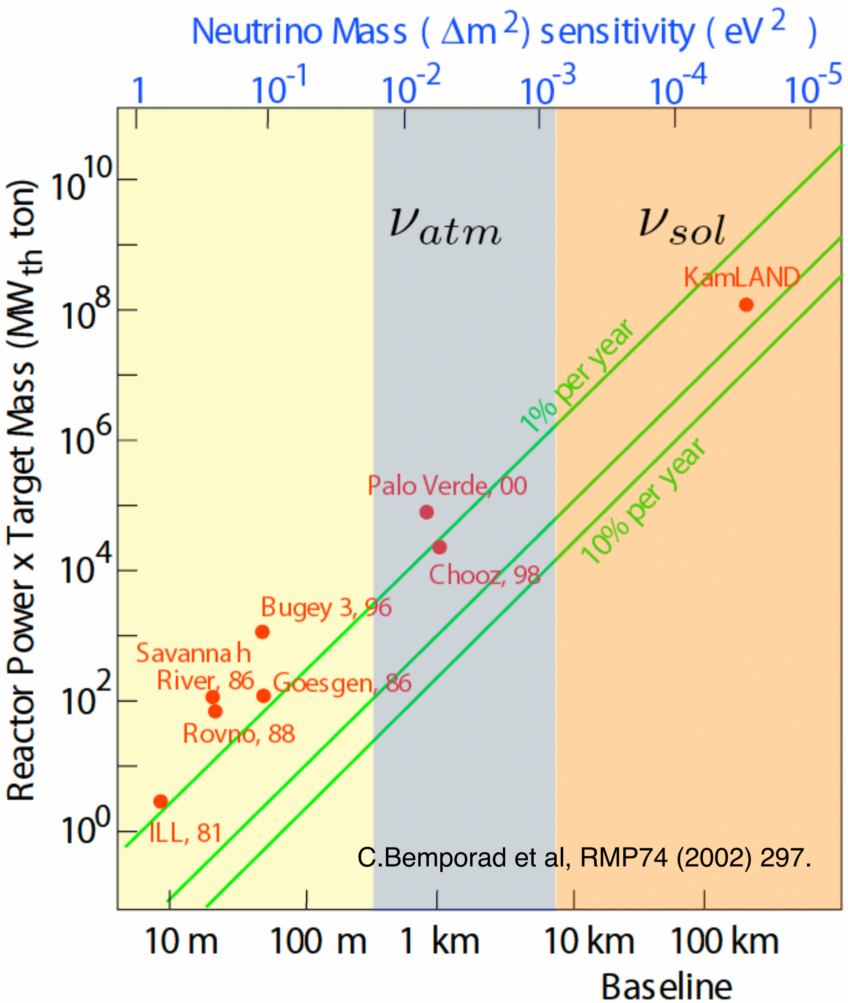
    $$E_{\overline{\nu}_e} \simeq E_{prompt} + 0.8MeV$$

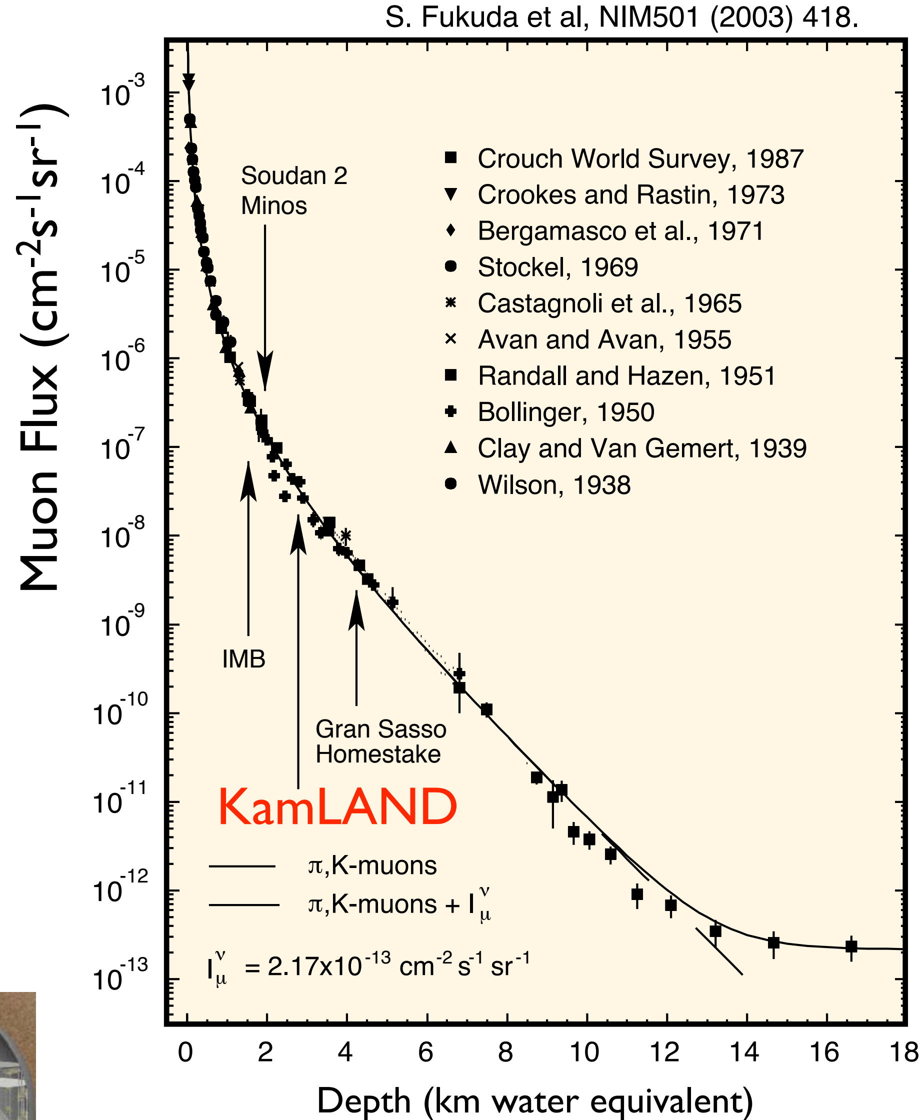
  - delayed event: neutron capture after ~210μs
    - 2.2 MeV gamma

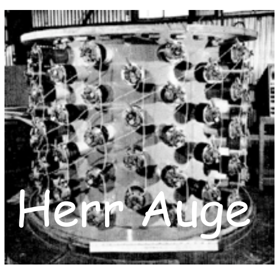
Delayed coincidence: good background rejection

The KamLAND Experiment

Long Baseline Means Large Detectors

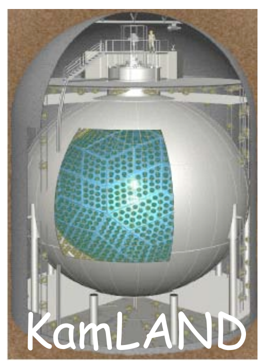






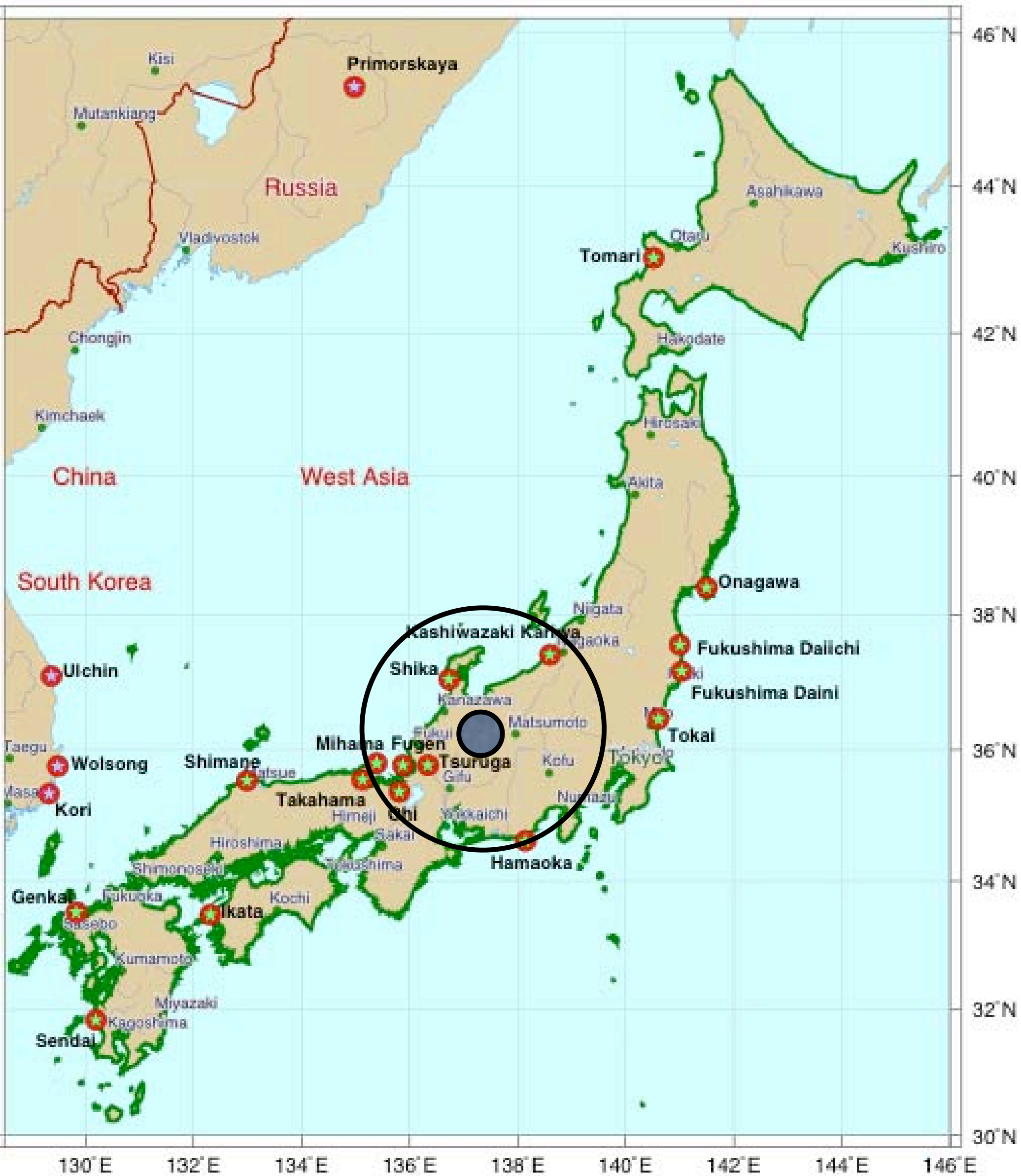
← 1m →

← 4m →



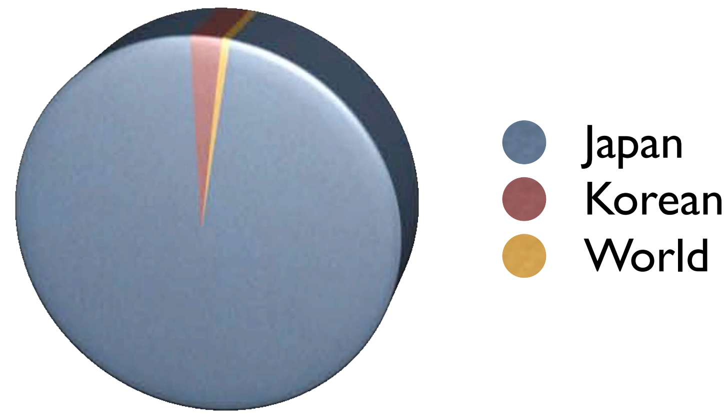
← 20m →

$\overline{\nu}_e$ from 53 Reactor Cores in Japan

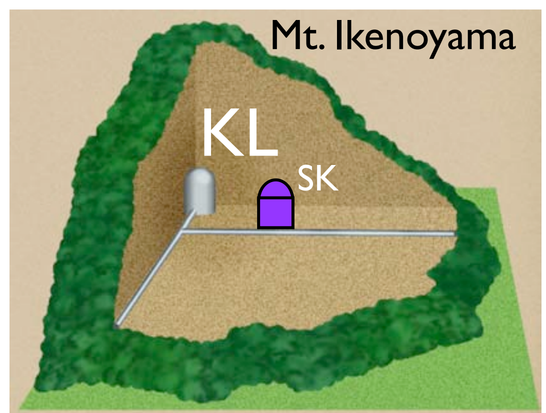


70 GW (7% of world total) is generated at 130-220 km distance from Kamioka.

Reactor neutrino flux: ~$6 \times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Effective distance ~180km

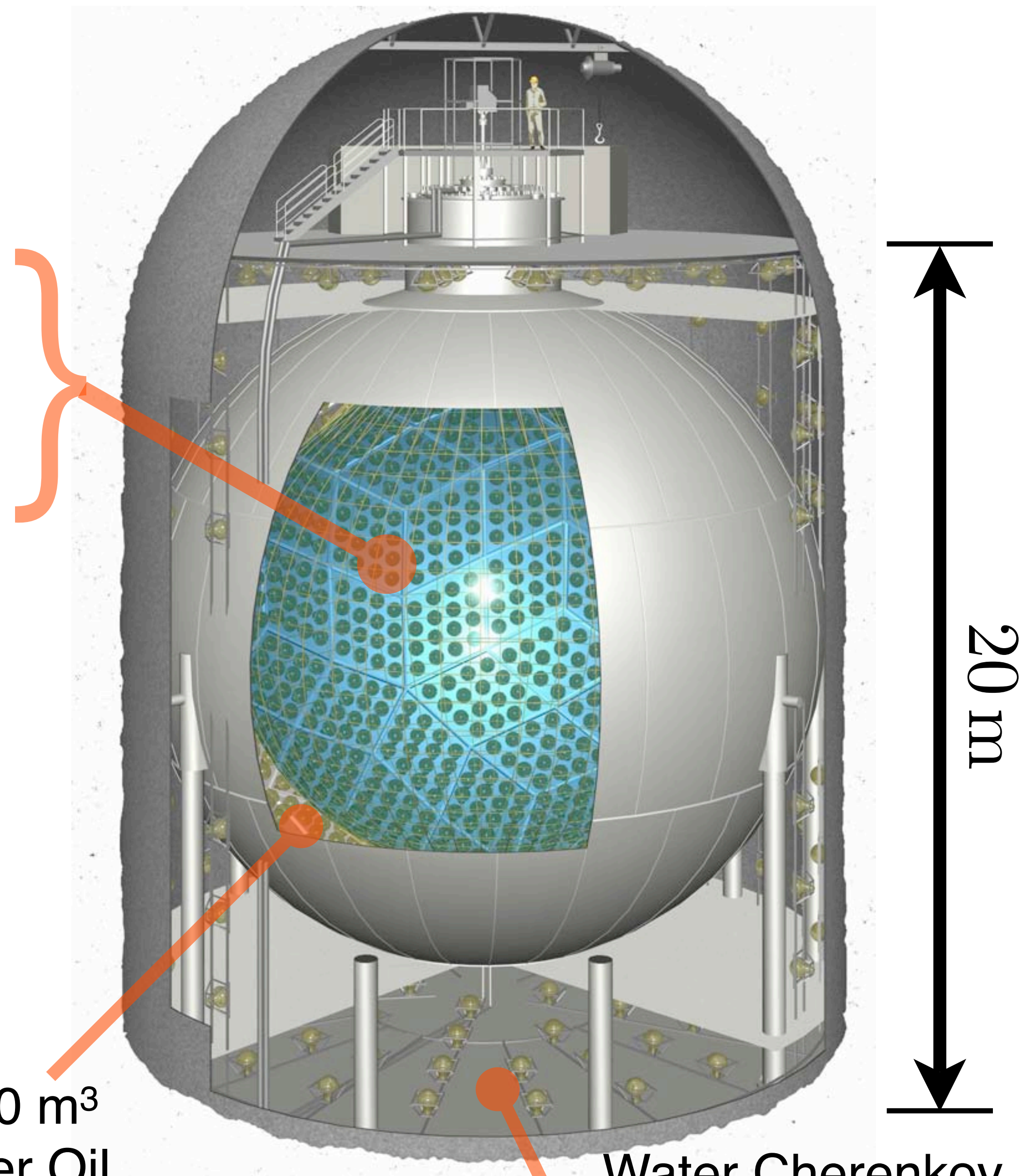


1000m rock
= 2700 mwe

long. $137°18'43.495''$
lat. $36°25'35.562''$
alt. $358\,\mathrm{m}$

KamLAND detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Multi-hit, deadtime-less electronics
- Water Cherenkov veto counter



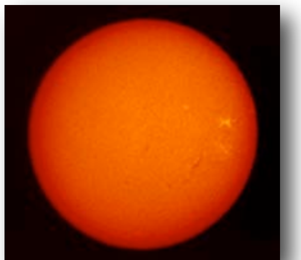
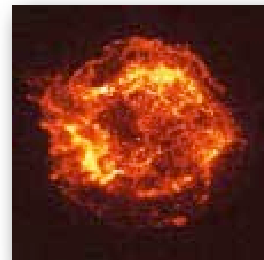
KamLAND Physics Capabilities

0.4 | 1.0 | 2.6 | 8.5 | Energy [MeV]

neutrino electron elastic scattering

$\nu + \mathrm{e}^- \rightarrow \nu + \mathrm{e}^-$

inverse beta decay $\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$

^{7}Be solar neutrino	geo-neutrino	reactor neutrino	supernova, relic neutrino, solar anti-neutrinos etc.
			
Neutrino Astrophysics	Neutrino Geophysics	Neutrino Physics	Neutrino Cosmology
Verification of SSM	Study of earth heat model	Precision measurement of oscillation parameters	Verification of universe evolution, SSM

Geoneutrinos
Nature 436, 499 (2005).

1st reactor result
PRL 90 021802 (2003).

2nd reactor result
PRL 94 081802 (2005).

Solar $\overline{\nu}_e$
PRL 92 071301 (2004).

Future
Low background
phase

Quite a few Reactors were Off

Nuclear safety scandal might benefit KamLAND

Power utility could face lower costs, writes **Bayan Rahman**

The admission last week by the world's largest private electric utility that it had falsified safety records at nuclear power plants has shaken the Japanese public's trust in the industry and is likely to make a dent in the company's finances.

But the long-term picture may be less bleak for Tokyo Electric Power (Tepco) and the sector if public pressure forces the government to curb its plans for new nuclear power plants, saving the utilities trillions of yen in construction costs.

Tepco announced this week it would shut five reactors that are still operating despite cracks in shrouds that surround the reactor core. The move follows its admission that there were 29 cases of data falsification at three nuclear plants in the 1980s and 1990s.

The closures came despite assurances from the Nuclear and Industrial Safety Agency

eration. One of the units, at Kashiwazaki Kariwa in Niigata prefecture, is likely to be shut for 80 days while the remainder will be closed for inspection for 40 days, costing the company about Y22bn ($188m) in higher fuel expenses.

Paul Scalise, analyst at Dresdner Kleinwort Wasserstein, estimates the closures will cost the company Y41bn, leaving the company 21 per cent short of its full-year net profit forecast of Y192bn.

But if the company decides to replace the shrouds at each of the five units, leading to longer closures, the fuel costs alone could increase to Y100bn, according to Lalita Gupta, analyst at Morgan Stanley.

"That the company will decide to exchange the shroud on all these five units remains highly questionable given the financial impact, fuel procurement issues and supply capacity

About 30 per cent of power supply is deregulated and the utilities are braced for further liberalisation.

At the same time, they are under instruction to build 13 nuclear power plants by 2012 as part of Japan's effort to cut greenhouse gas emissions, while new entrants are free to use cheaper sources of energy. Tepco is due to begin construction of a power plant in Fukushima prefecture in 2007 at a cost of Y433bn, followed by another unit a year later. Ennet, a new entrant, is building an LNG (liquefied natural gas) plant in Ibaraki prefecture for just Y10bn.

"The utilities are forced to deregulate and at the same time to build these behemoths. Meanwhile, the government is not willing to give them subsidies," says one analyst. "The companies have been looking for a way out."

Tepco has been slow to cut costs despite deregulation

Falsified records: Tokyo Electric Power's president, Nobuya Minami, has resigned AP

Neutrino Oscillation Results

Reactor Neutrino Data Summary

THIS RESULT

from 9 Mar 2002 to 11 Jan 2004
515.1 live days, 766.3 ton-year exposure
×4.7 exposure (×3.55 live time, ×1.33 fiducial)

expected no-osc signal	365.2 ± 23.7
BG	17.8 ± 7.3
observed	258

Neutrino disappearance at 99.998% CL.

$R = 0.658 \pm 0.044(stat) \pm 0.047(syst)$

$R = 0.601 \pm 0.069(stat) \pm 0.042(syst)$
for Mar to Oct 2002

(consistent with first result)

KamLAND collaboration, Phys.Rev.Lett 94 081802 (2005).

EARLIER RESULT

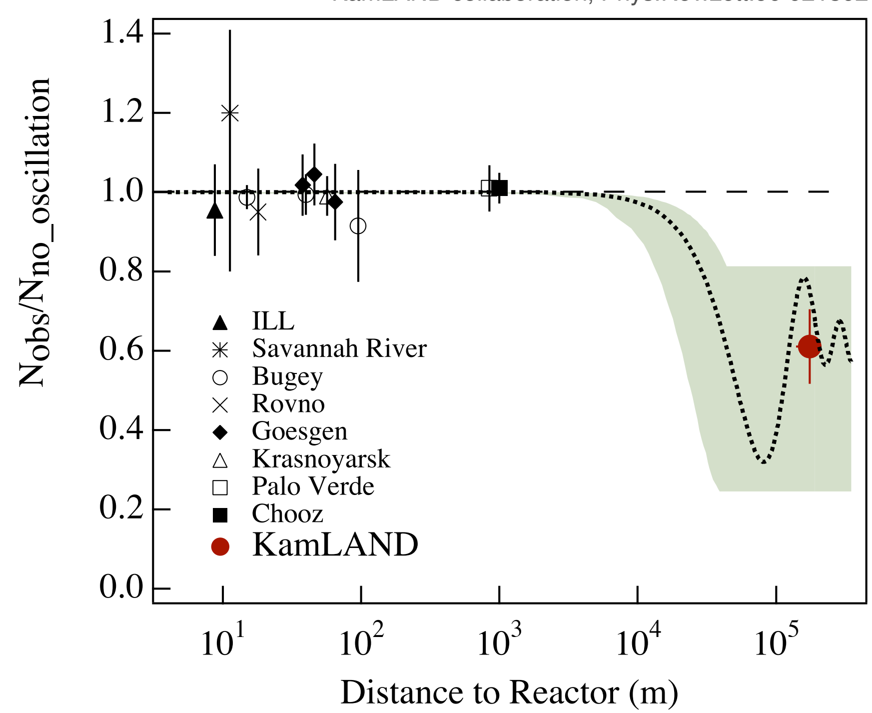
from March 4 to October 6, 2002
145.1 live days, 162 ton-year exposure

expected signal	86.8 ± 5.6
BG	1 ± 1
observed	54

Neutrino disappearance at 99.95% CL.

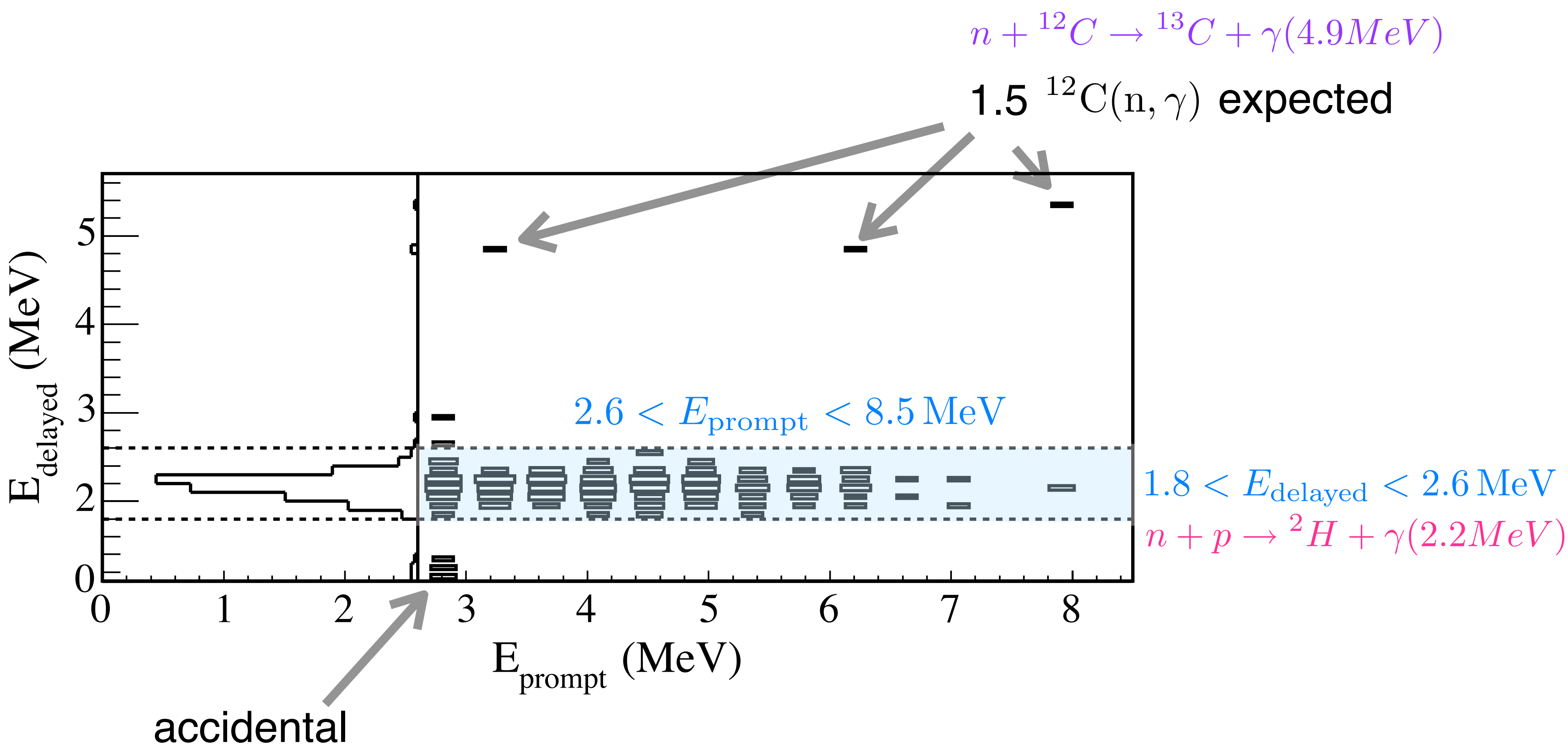
$R = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$

KamLAND collaboration, Phys.Rev.Lett.90 021802 (2003).

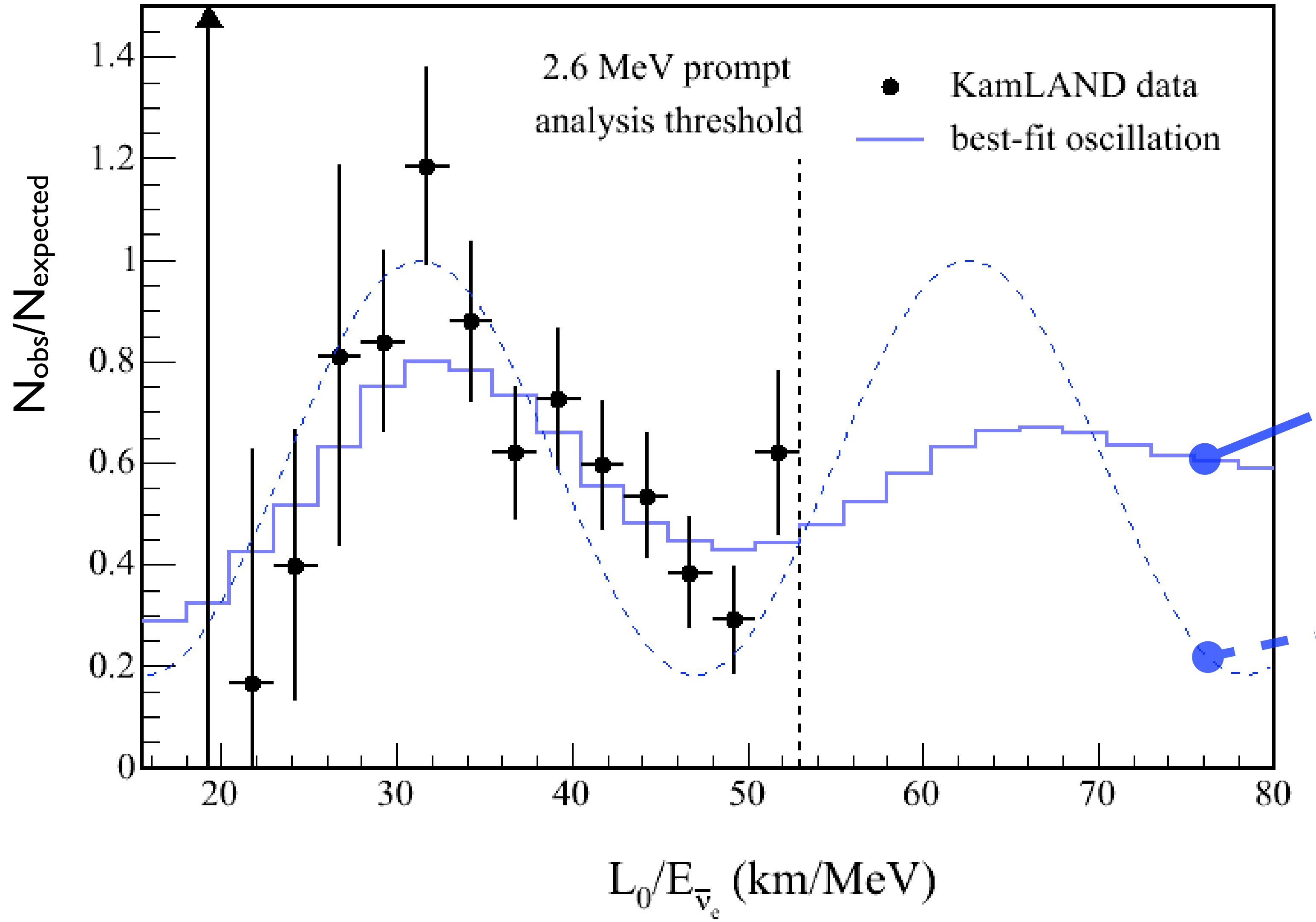


Caveat: ratio does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

Delayed Coincidence



Clear delayed coincidence events



Best-fit oscillation accounting for energy spectrum and reactor distribution

Oscillation pattern for a $\overline{\nu}_e$ of 4 MeV energy

Ratio of measured to expected no-oscillation spectrum

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right)$$

Can KamLAND Detect a Nuclear Test?

North Korea tested a nuclear device on Oct 9, 2006: can KamLAND detect a test of a nuclear weapon?

- Assume a test of a Hiroshima size bomb (~15kton TNT) or ~10 kg of fissile material
  - Larger bombs are detectable by other means
- Further assume:
  - All material is fully fissioned
  - Distance is ~1000km from KamLAND (across the Japanese Sea)
- Typical 3GW (thermal) reactor has a few tons of fissile material burned up in a cycle of ~18months → 10kg/day
- KamLAND measures anti-neutrinos from 53 1GW size reactors, at a rate of ~1 anti-neutrino/day at avg. distance of ~200km

A small nuclear device will generate <0.001 of an additional anti-neutrino event in KamLAND

Geoneutrino Results

Deconstructing Earth

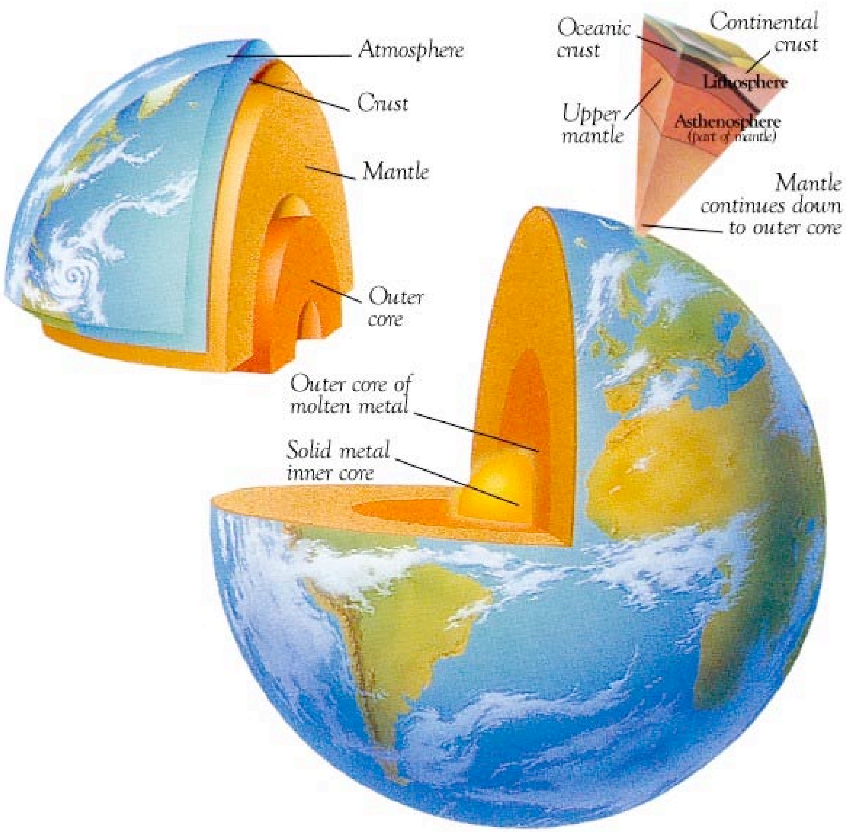
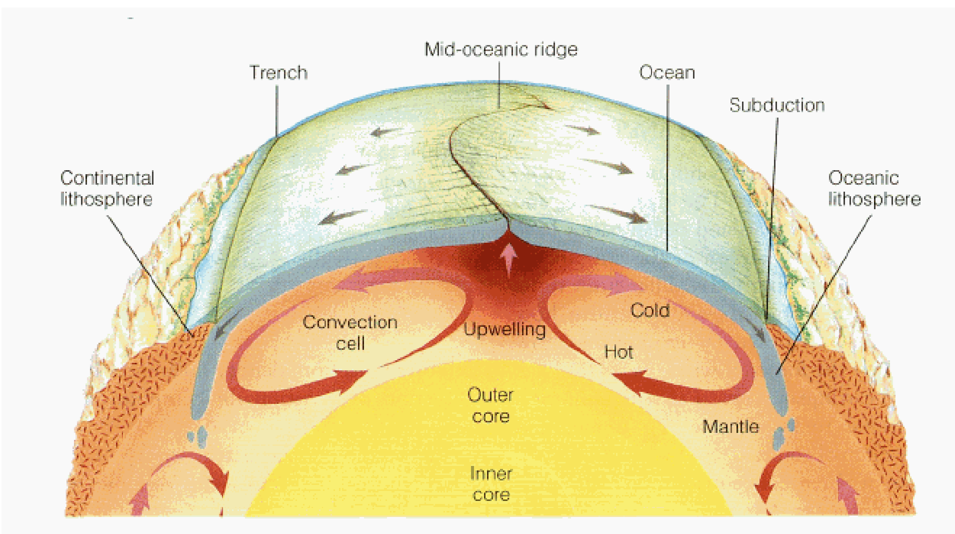


Image by Colin Rose and Dorling Kindersley

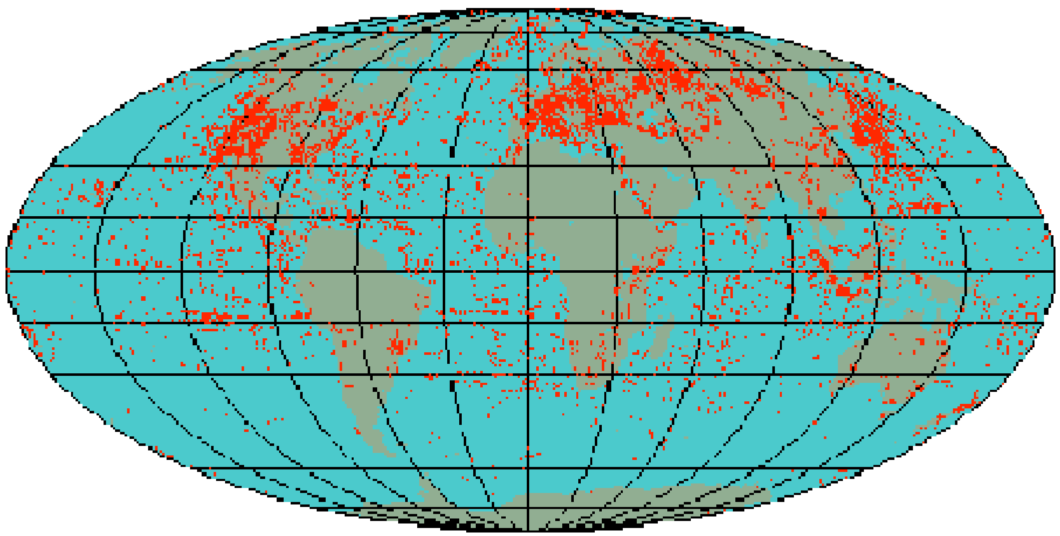


- Seismologists subdivide the Earth into five basic regions:
  - Core
  - Mantle
  - Oceanic crust
  - Continental crust
  - Sediment
- These regions are solid except for the outer core
- Oceanic crust is made at mid-oceanic ridge and recycled at continental trenches

Where does the energy for convections, plate tectonics, etc. come from?

Earth Heat Flow

Bore hole locations



Heat Flow

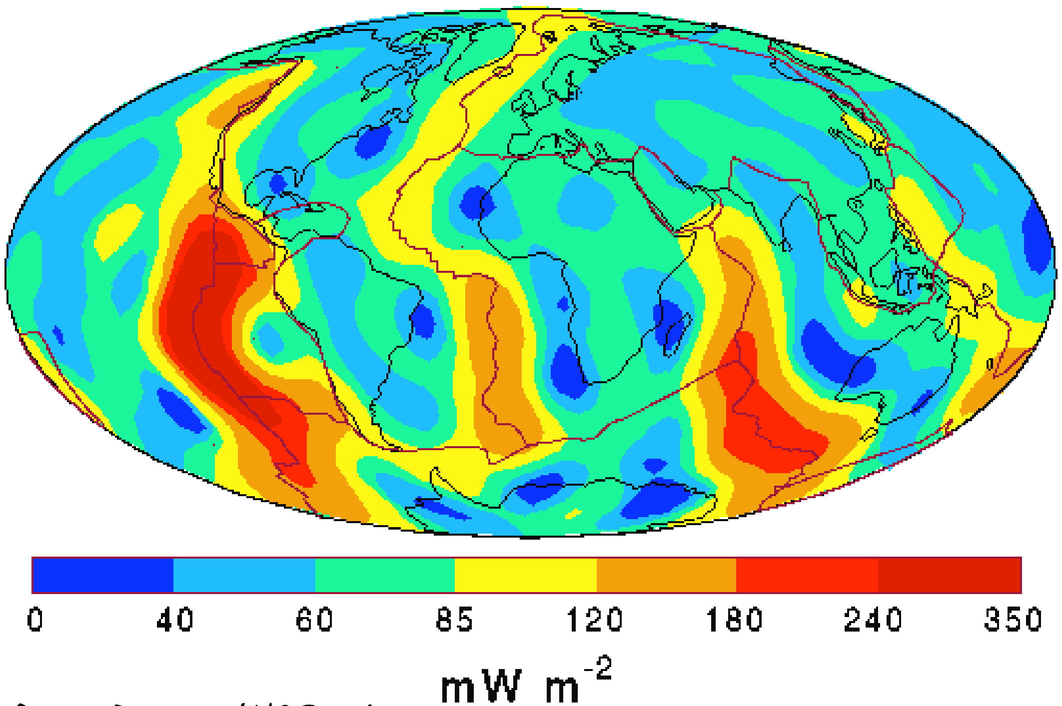


Image from Pollack et al.

- Based on bore holes measuring conductive heat flow (need temp gradient and conductivity):
  - Total heat flow of 44±1TW
  - 40 times larger than total world reactor power
  - Average heat flux: 87 mW/m^2
  - (a more recent calculation estimates it to be 31±1TW)
- Where does this heat come from?

Radiogenic Heat

How much do radioactive decays contribute to heat?

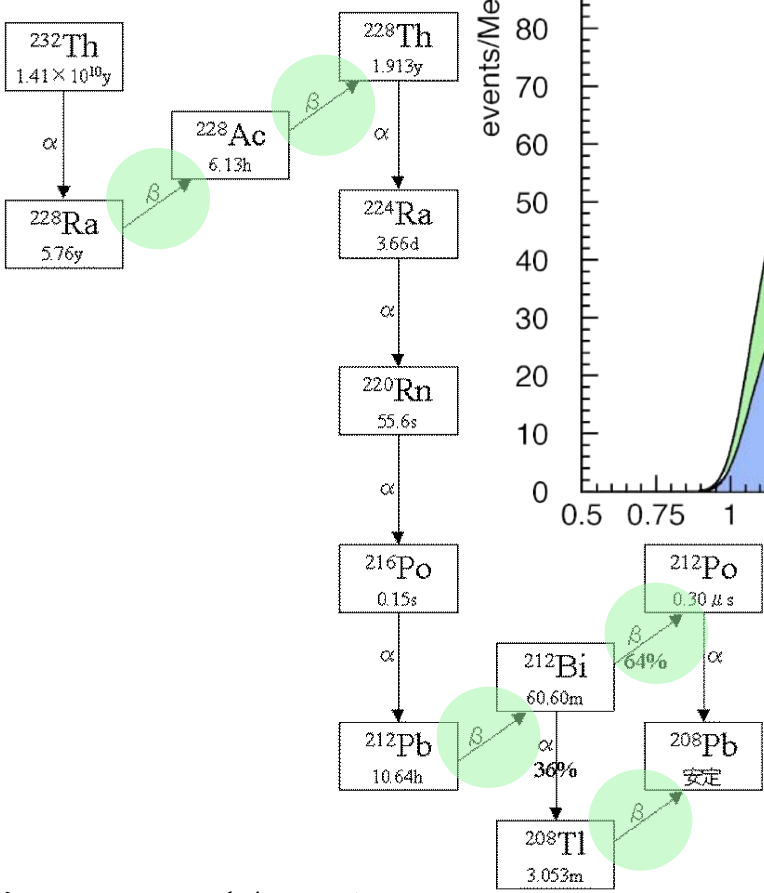
- Abundances of elements in Carbonaceous Chondritic meteorites are similar to those in the solar photosphere
- Composition of Earth should be similar to these chondrites
- These chondrites contain U, Th and K and therefore there should be similar concentrations in the Earth
- From these meteorites, we know the Th/U ratio to be ~3.9
- **U, Th and K decay and in one reference model**:
  - Uranium and Thorium account for 8TW each
  - Potassium is 3TW

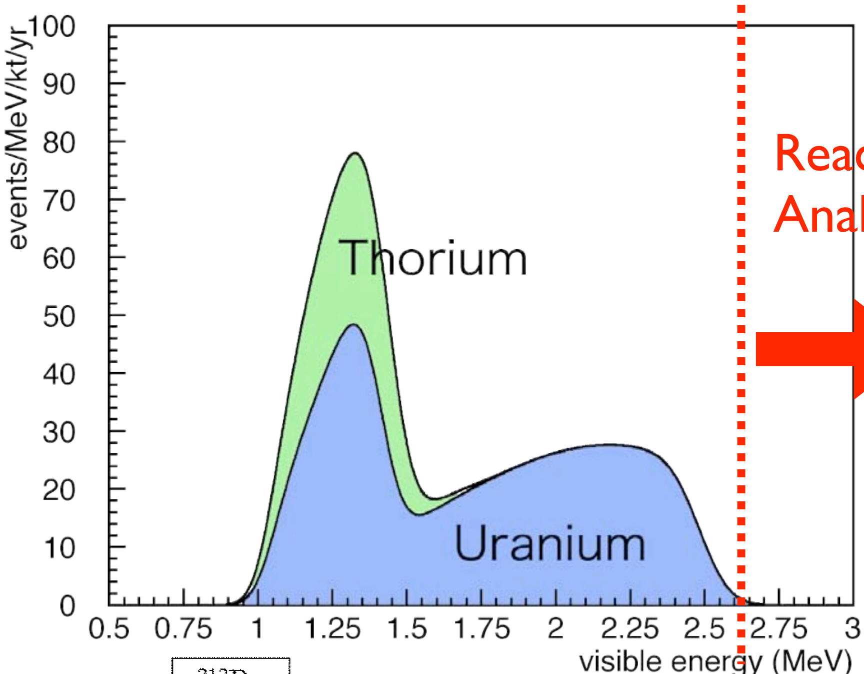
  } Total radioactive power: 19TW
- Rest of Earth heat is 'old' heat
  - Accretion heat
  - Latent heat from core solidification

Geoneutrinos

Neutrinos from radioactivity provide direct information on the Earth's interior

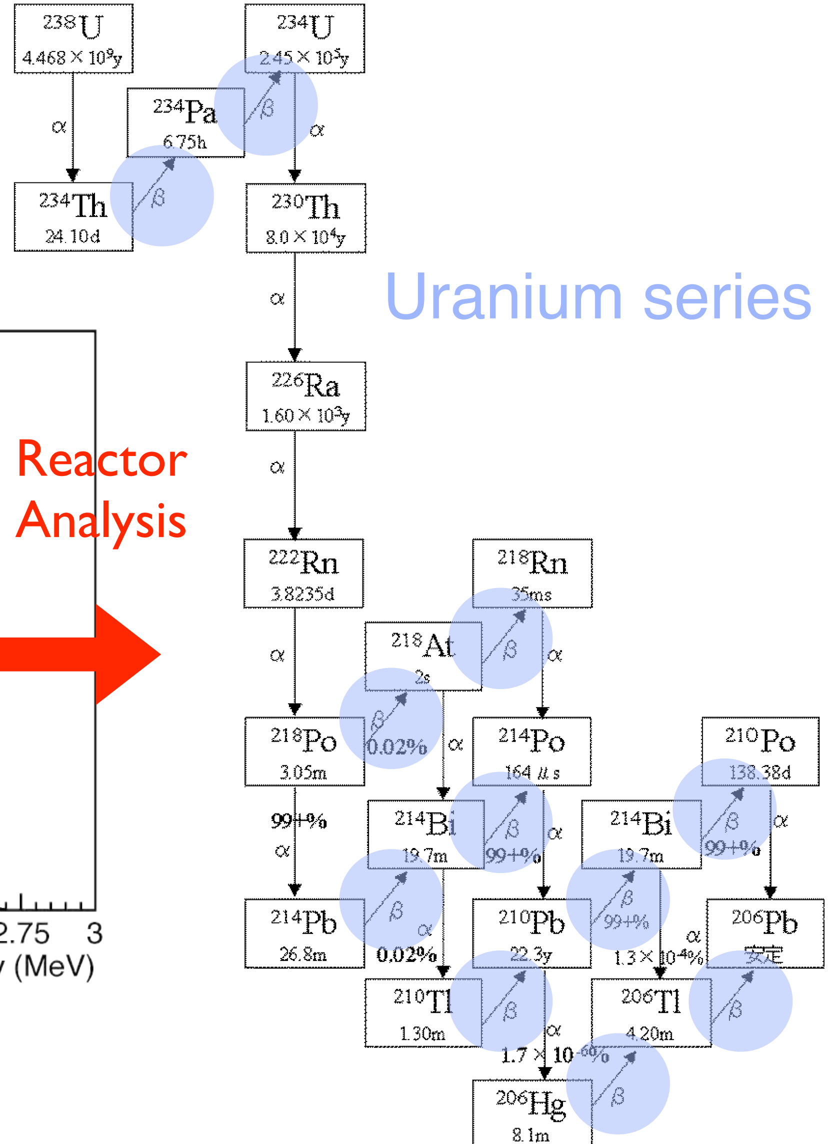
Thorium series





Reactor Analysis

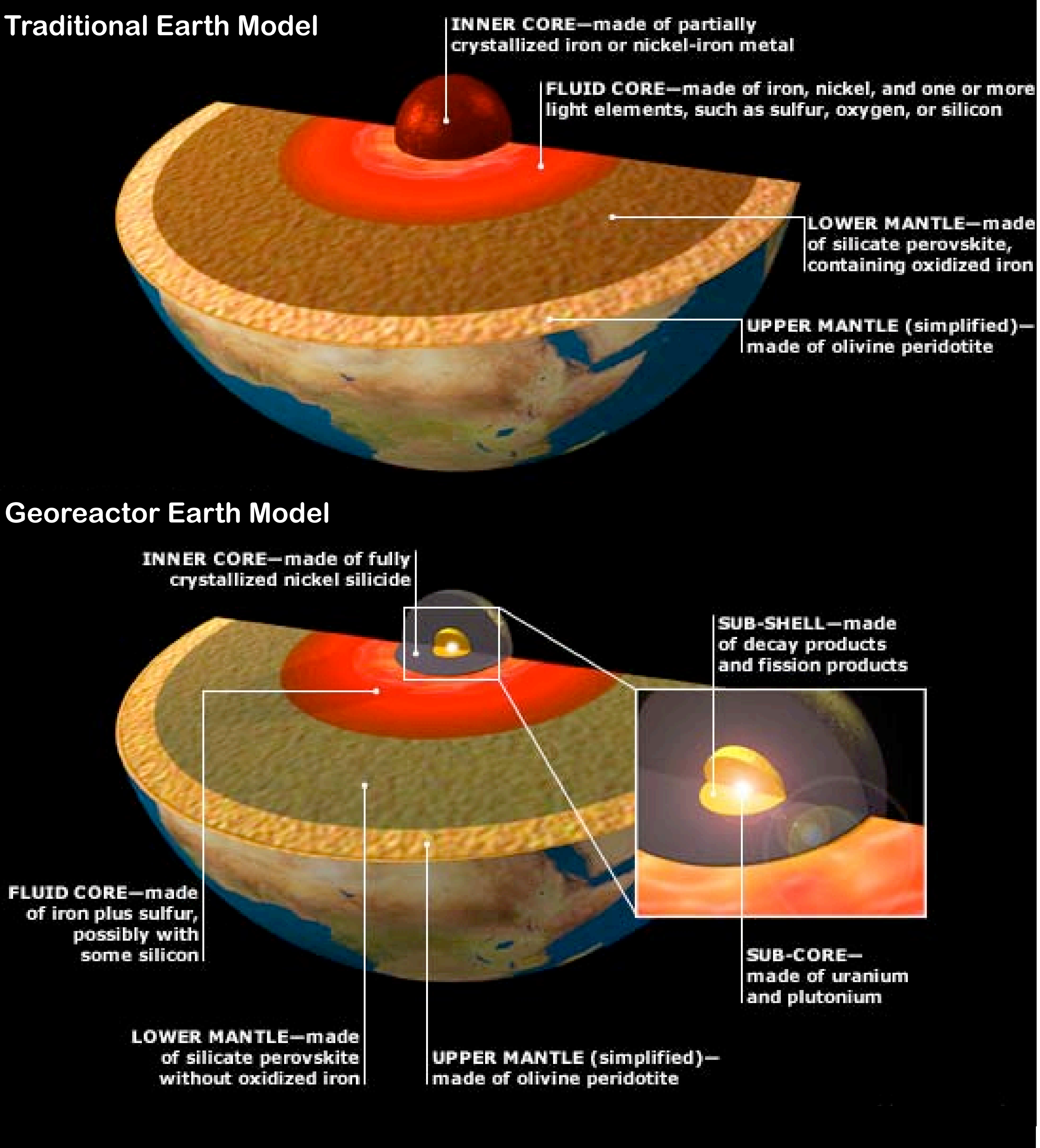
Uranium series



Potassium not visible, because it's below inverse beta-decay threshold of 1.8MeV

Geologically Produced Neutrinos

- Two (potential) sources of geologically produced neutrinos:
  - Antineutrinos from radioactive decay chains ← Geoneutrinos
  - Antineutrinos from a hypothetical reactor at the Earth's center

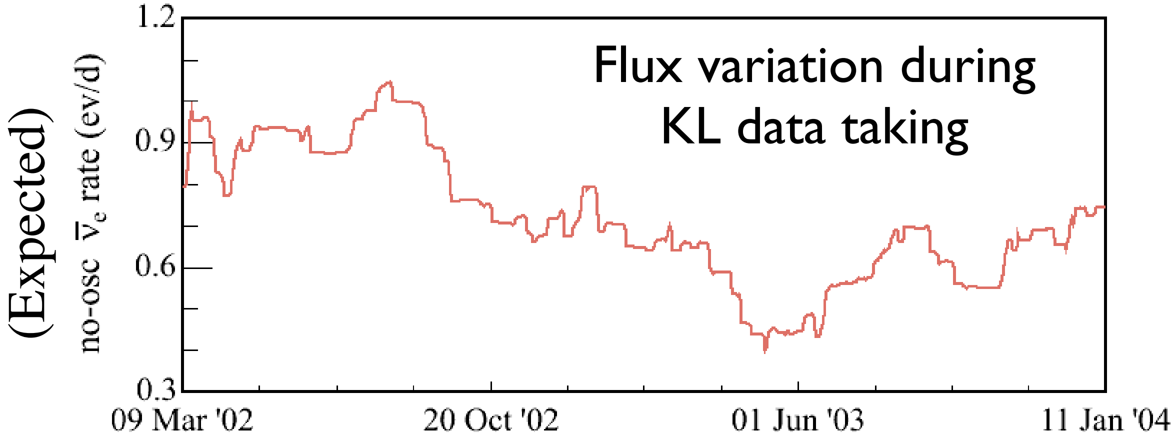


By Matt Zang, Discover Mag, Aug. 2002.

- Georeactor definitely not mainstream theory
- Primarily based on the observation that the $^3He/^4He$ high at some volcanic plumes
- Oklo natural reactor 2 Gy ago ($^{235}U/^{238}U$ ratio)
- 10-15 km nuclear core
- 3-10TW of heat output
- Should produce anti-neutrinos according to reactor spectrum

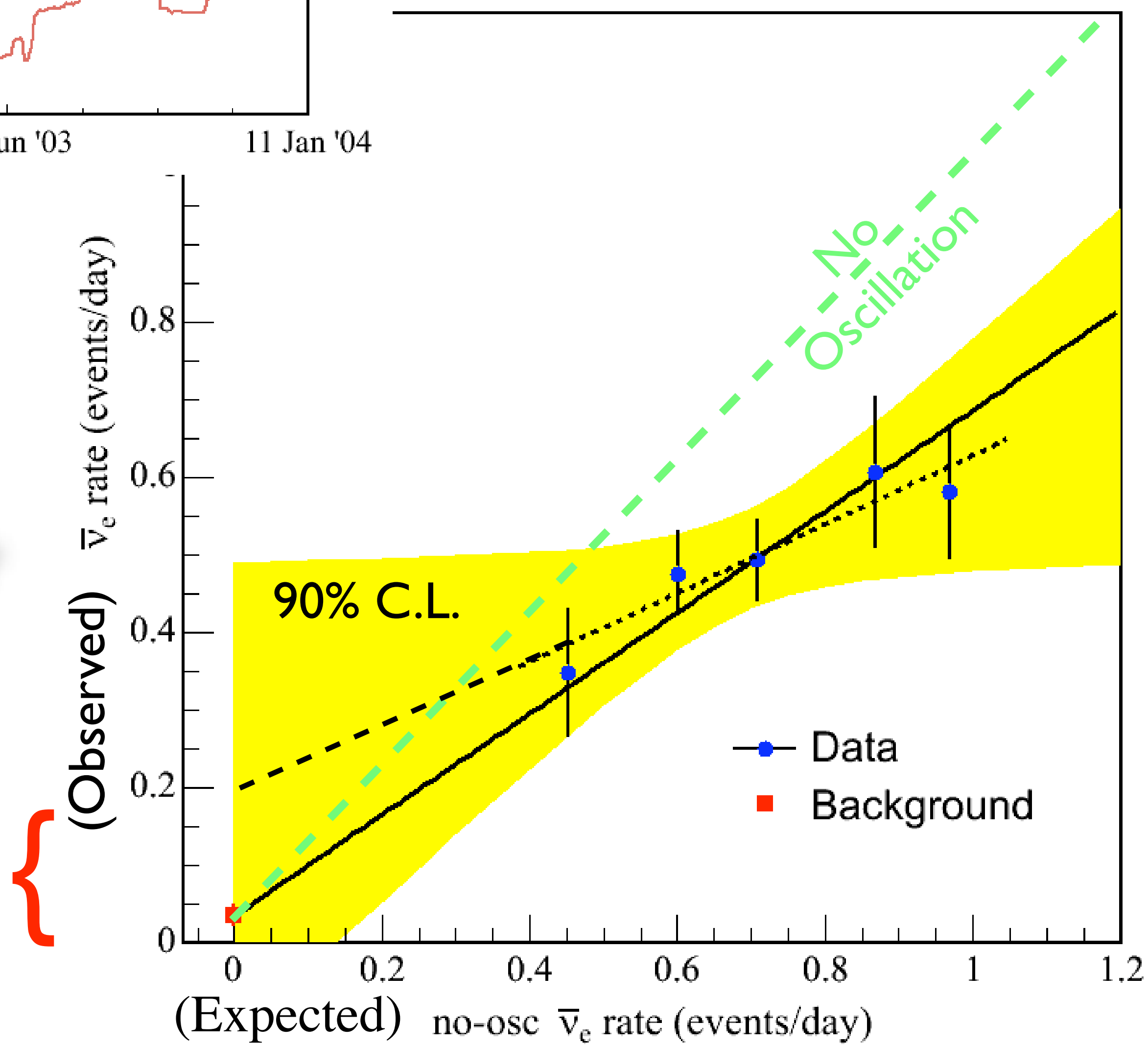
5-15% of ‘Manmade’ reactor spectrum at KamLAND

Investigating a Hypothetical Georeactor



Statistics not good enough to make firm statements on correlation or georeactor

Georeactor < 19TW at 90% C.L.



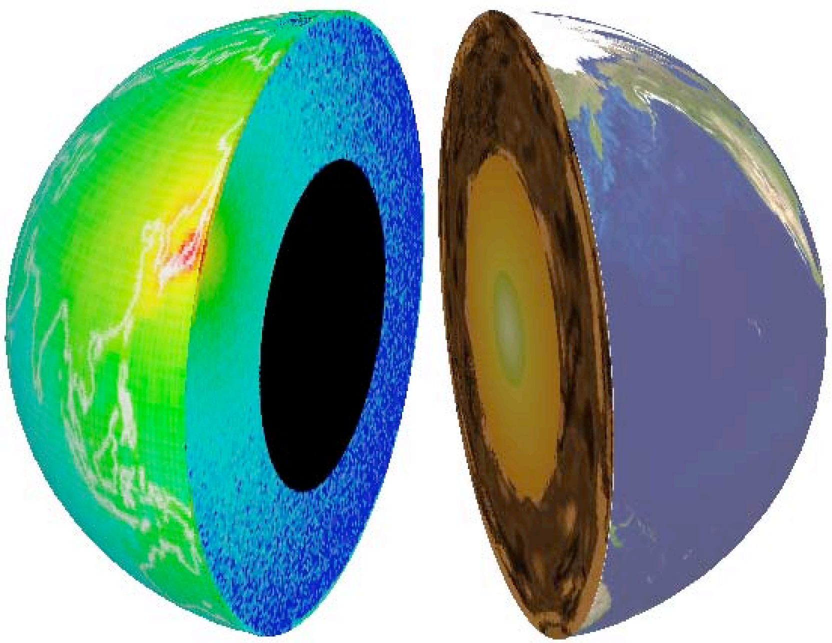
Geoneutrino results

Rate analysis of the geoneutrino result:

152 observed candidate events

127±13 background events

$\Bigg\}$ 25^{+19}_{-18} geoneutrinos



BSE Reference Model: 19±4

A Mining Analysis' View of Geoneutrinos

"Geology and Applications in Mining"

Conclusion
Nature Journal says that "Future observations at KamLAND, and at the Borexino detector under the Gran Sasso mountain in central Italy, which begins operation in 2006, will generate more data and provide greater sensitivity in testing the nature and sources of geoneutrinos."

"Before the revolution really comes to fruition, I think it'll take some time," Gratta told Live Science, "I would imagine one or two decades, before we have more of those detectors and maybe larger ones built in the appropriate place for geophysics."

Clearly this is still some time off commercial application in the mining sector, and these scientists probably aren't too concerned with how this could improve exploration success like 3-D seismic has done for oil and gas. They are looking at things like the heat of the earth's core.

But when the BHP's of this world get their hands on this, they could well put it to good use, as long as it doesn't have the unintended consequence of scaring up too many new deposits and depressing commodity prices.

Either way, it will make for an interesting future. Science buffs can access the tremendously complicated results of the KamLAND study here.

How NERSC helped us get our results out

KamLAND use of NERSC

- Collaboration is subdivided into 2 subgroups:
  - Japan: Tohoku University in Sendai (about 35 collaborators)
  - US: 10 Universities/Institutes:
    LBL, UC Berkeley, Stanford, Caltech, U of Alabama, U of Tennessee, Drexel, U of Hawaii, TUNL, Kansas State (about 45 collaborators)
- Main computing center for US is NERSC
  - KamLAND has about a 10% share of the PDSF computing resources
  - 18TB of central disk - most of it converted to GPFS
    - GPFS has really improved things for us compared to NFS!
  - HPSS used for archival storage

Data Rates

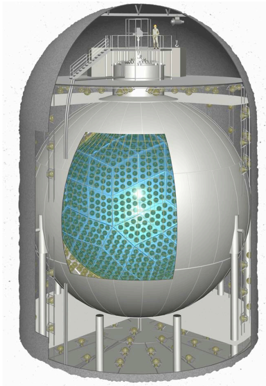
- KamLAND Trigger Rate: 40 Hz
- Reactor anti-neutrino rate: 1 every 2 days!
- KamLAND takes data 24/7, 365 days per year
- HPSS Storage requirements: 250GB/day
- Analysis of the data is done on PDSF
  - Event reconstruction consists of event vertex finding, energy calibration and reconstruction, muon track fitting etc.
  - 2nd stage reconstruction consists of finding event correlations

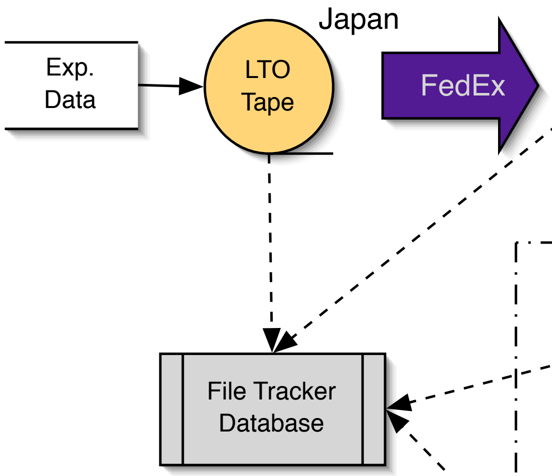
Finding a needle in a haystack

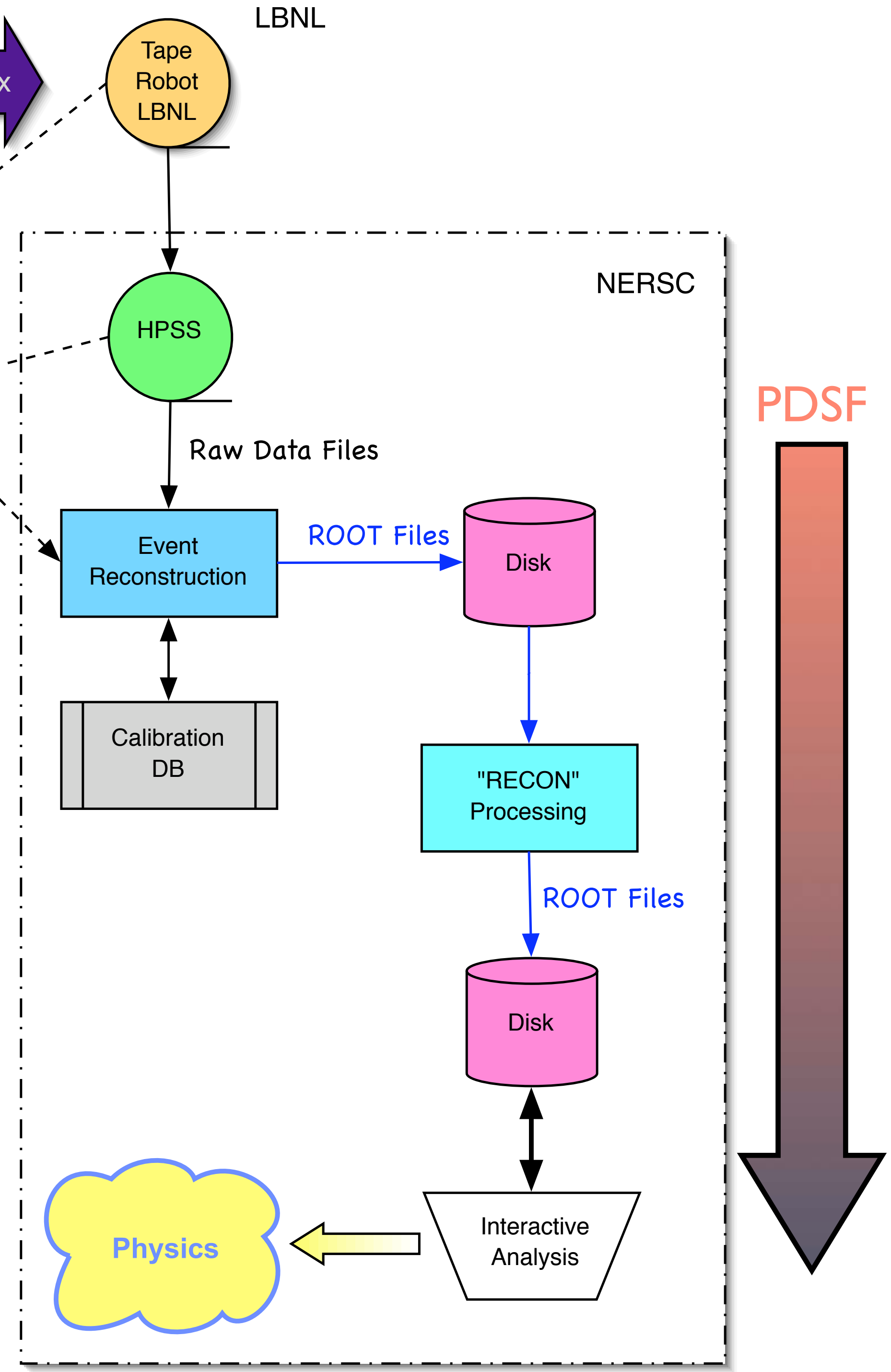
Data Analysis Software

- All software written in C++
  - ~60000 LOC
- External software:
  - ROOT framework - very tight integration
  - PostgreSQL client libs
- Some of our algorithms:
  - Pulse finding, FFT, log likelihood fitting, track finding, iterative algorithms...

KamLAND Data Flow

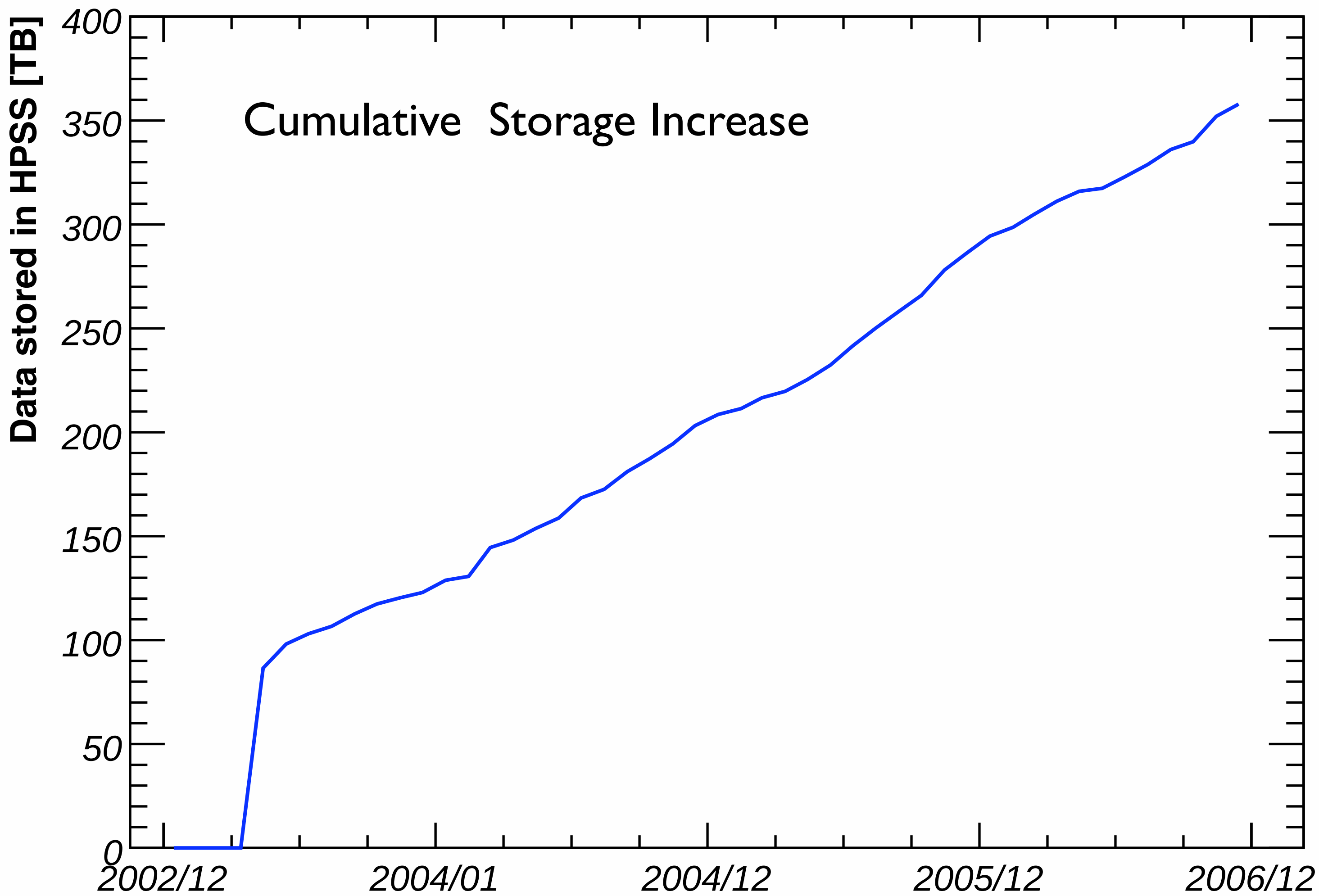






- PDSF is the main KamLAND analysis facility for the US collaboration
- Critical in the analysis of all KamLAND papers
- Strength is the synergy of two NERSC systems:
  - **PDSF**: batch, interactive jobs
  - **HPSS**: data storage

KamLAND HPSS Usage at NERSC

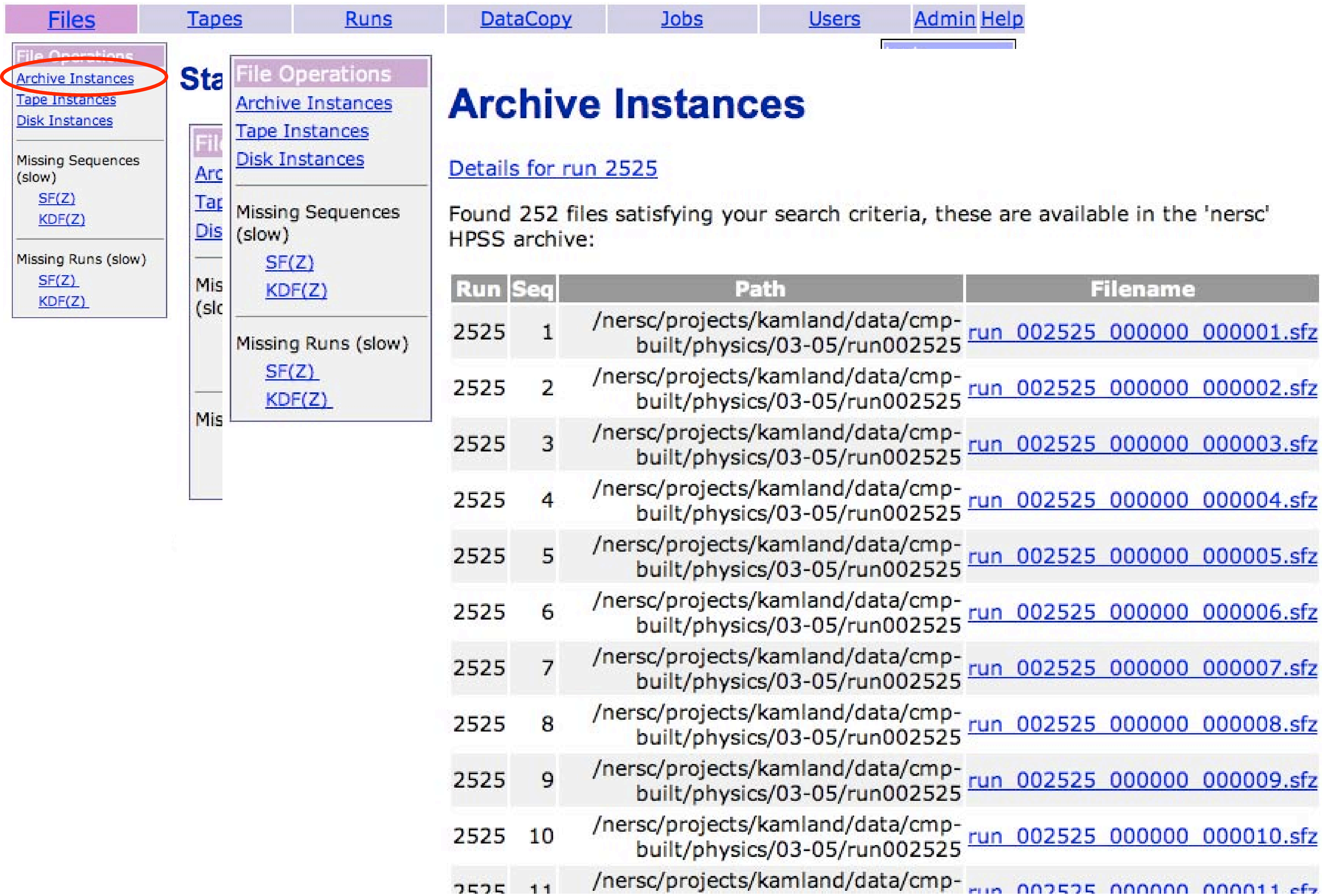


KamLAND is the 2nd largest HPSS user at NERSC:
3M SRU awarded for AY07

File Tracker Data base

- Produce about 1000 files a day
- Files are stored on LTO tapes, HPSS, disk or being copied through network data transfer: Need exact accounting of where what file is
  - Scientific data is what we are ALL here for!
- Use a home grown File tracker DB for accounting
  - Implemented in PostgreSQL
  - Web interface for casual inspection
  - API: perl and C++

Easy Interface to all Data


Files | Tapes | Runs | DataCopy | Jobs | Users | Admin | Help

File Operations
Archive Instances
Tape Instances
Disk Instances

Missing Sequences (slow)
SF(Z)
KDF(Z)

Missing Runs (slow)
SF(Z)
KDF(Z)

Archive Instances

Details for run 2525

Found 252 files satisfying your search criteria, these are available in the 'nersc' HPSS archive:

Run	Seq	Path	Filename
2525	1	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000001.sfz
2525	2	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000002.sfz
2525	3	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000003.sfz
2525	4	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000004.sfz
2525	5	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000005.sfz
2525	6	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000006.sfz
2525	7	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000007.sfz
2525	8	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000008.sfz
2525	9	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000009.sfz
2525	10	/nersc/projects/kamland/data/cmp-built/physics/03-05/run002525	run_002525_000000_000010.sfz
2525	11	/nersc/projects/kamland/data/cmp-	run_002525_000000_000011.sfz

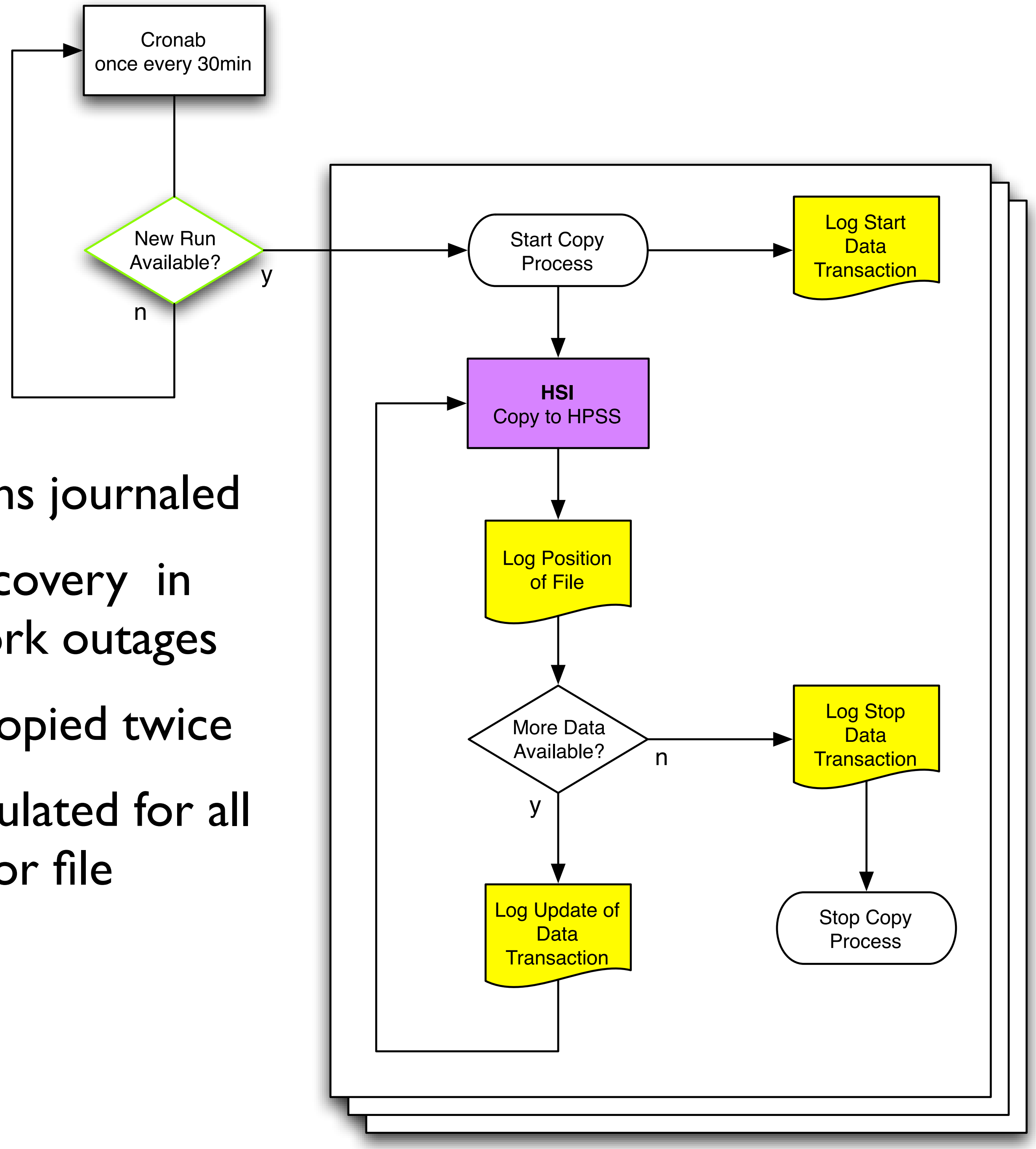
Tape Data Transfer

- From Jan 2002 to Oct 2006 used LTO tapes for data transfer
- Tape copy station in Japan and tape robot at LBL
  - Weekly FedEx box with tapes from Japan to LBL
- ~6000 LTO tapes read in the past 5 years
- Data read failure rate ~2%
  - Probably mostly due to bad shipment packaging
  - Reuse of tapes: some tapes were reused 10-12 times (i.e. 12x2x5300mi = 130k airmiles!)

Network Data Transfer

- We had a significant network upgrade in Summer 2006
- Decided to get rid of tape copy system
- Network performance:
    - Raw measured network performance: 100Mbits/s
    - Ping RTT: ~250ms
    - Single instance HSI performance: 1.5MB/s
- To fully utilize the bandwidth, we use up to 4 simultaneous HSI sessions: ~5-6 MB/s

Details of Network Transfer



Up to 4 HSI sessions

- All transactions journaled
- Automatic recovery in case of network outages
- No files are copied twice
- MD5sum calculated for all files to monitor file corruption

Datacopy Web Interface

Files | Tapes | Runs | DataCopy | Jobs | Users | Admin | Help

Copy Operations
- Last 24 hours
- Last 1 week
- Last 4 weeks
- Last 8 weeks
- Last 12 weeks
- All

Login
You are logged in as **decowski**
Logout

Data Copy Status

This page summarizes the progress of the Mozumi -> NERSC KamLAND data copy process.

53 copy processes in the past 7 days, avg. total copy rate was 2.995 MB/s.

Run	Type	Started At (JST)	Ended At (JST)	Last Update (JST)	Files	Tot. Bytes	Avg. Rate (MB/s)
6711	SFZ	2007-03-21 09:30:12+09	2007-03-22 01:09:23+09	Done	248	6.53544e+10	1.106
6711	KDF	2007-03-21 09:30:12+09	2007-03-22 04:26:51+09	Done	284	7.47192e+10	1.045
6710	KDF	2007-03-21 04:30:13+09		2007-03-22 08:38:53+09	414	1.10059e+11	1.036
6710	KDF	2007-03-21 04:00:16+09			0	0	
6710	SFZ	2007-03-21 04:00:14+09	2007-03-22 01:27:02+09	Done	324	8.60606e+10	1.063
6710	KDF	2007-03-21 03:30:15+09			0	0	
6710	KDF	2007-03-21 03:00:23+09			0	0	

Run being copied

Down due to HPSS maintenance period (every Tue PDT)

20TB already copied through network!

Future Usage / NERSC Requests

- Next is solar phase: KamLAND will study neutrinos coming from the Sun. This will help us understand how the Sun shines
  - Data rate increase: from 250GB/day to ~400GB/day
  - We plan on expanding our disks from ~18TB to 40TB
  - Plan using ~70k SI2K for analyzing our data
- Things that would help us:
  - Production accounts: one account for running our production
  - Get rid/increase the O(20) simultaneous HPSS connection limitation
  - New technologies: local expertise of PROOF (parallel ROOT)

Some KamLAND Publications

References

	#Citations
[1] K. Eguchi *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **90**, 021802 (2003).	1294
[2] K. Eguchi *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **92**, 071301 (2004), [arXiv:hep-ex/0310047].	73
[3] T. Araki *et al.* [KamLAND Collaboration] Phys. Rev. Lett. **94**, 081801 (2004), [arXiv:hep-ex/0406035].	443
[4] T. Araki *et al.* [KamLAND Collaboration] Nature **436**, 499-503 (2005).	40

NERSC has made it possible for us to do all these publications and produce **Great Science**

THANK YOU!